



 Luminous — Knowledge Share Public Report

ARENA Solar ScaleUp (PRO-2509) — KS2.1 (DL-20173)
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EXECUTIVE SUMMARY

Luminous Robotics **successfully deployed** a fleet of LUMI Series 4 systems which supported robotically installing modules at the 319MWp Goorambat East Solar Farm (GESF), built by Equans Solar & Storage Australia and Bouygues Constructions Australia. These robots help complete its scope of work on Block 27 of the solar farm, **exceeding target production rate** at 103% — with key data & flow insights to shockingly increase nameplate capacity towards 246%. as the site completed module installation **ahead of schedule**.

This project is the first awardee of Australian Renewable Energy Agency (ARENA)'s \$100M Solar ScaleUp Challenge.

The purpose of this document is to report the challenges and lessons learnt during this project where Luminous achieved its most aggressive logistics, manufacturing, and field deployment timeline to date—from the United States to delivering impactful robotic systems to Australia, all the way across the world.

The developer ENGIE provided a number of press releases on the aftermath of the successful pilot of the LUMI fleets. Resulting in a number of local and global articles discussing the completion of the first phase of this project.



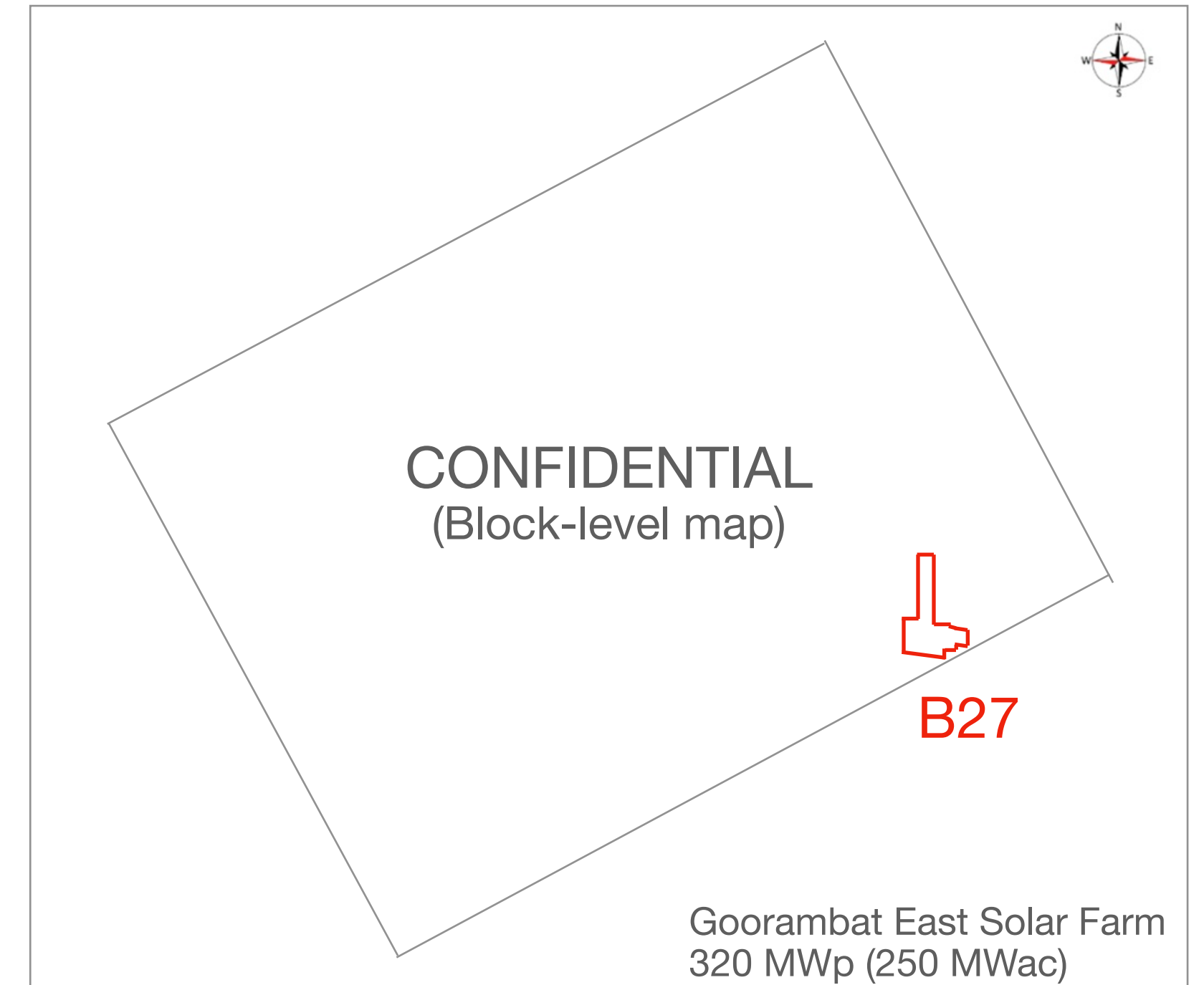
This LUMI project has made global press with the gracious support of ARENA.

PROJECT OVERVIEW

Phase I Pilot LUMI. Luminous Robotics Pty Ltd has partnered with Bouygues Construction Australia and Equans Solar & Storage Australia to demonstrate the LUMI Series 4 robotics fleets at Goorambat East Solar Farm, a 320 MWp (250 MWac) solar farm located in VIC Australia with 517,776 LONGi solar modules (615-620W).

Equans supported the project with laborers to catch, fasten, and inspect the modules being thrown by the LUMI robots. Each LUMI robot was paired with a single laborer who served as the catcher. Equans also had a skid steer onsite which supported the logistics of the pallet of modules for the LUMI robots down the rows.

Luminous provided two LUMIs and two onsite robot operators. Later in the project Luminous also rented a skid steer and two skid steer operators such that both robots can simultaneously traverse down the rows with skid steers with the pallets.



HOW THE PROJECT OUTCOMES WERE ACHIEVED

Luminous partnered with **Rohlig Logistics** to support global and domestic transport of components, assemblies, and robots between USA and Australia and later, transporting finished LUMIs from warehouse to construction site.

Rohlig provided Luminous with a working area within their state of the art **18,500 square meter facility** for manufacturing, assembly, and testing of the two LUMIs. Major kits were assembled at Luminous USA and shipped overseas by Rohlig.

Two assembled LUMI robots were transported to Goorambat near B27 where a tented area was set up to maintain and charge the robots overnight.

Equans provided Protech laborers, who were responsible for nuts & bolts, torque gunning, alignment, and rubbish. Luminous provided **two LUMI robots** and two Robot Engineers. Further, Luminous supported the Wet Rentals and skid steer operators for the nominal flow of work.

Rohlig Warehouse //



Goorambat East Solar Farm //



PERFORMANCE METRICS



LUMI Engineer - complementary via Luminous' Wet Rental

Laborer - Protech

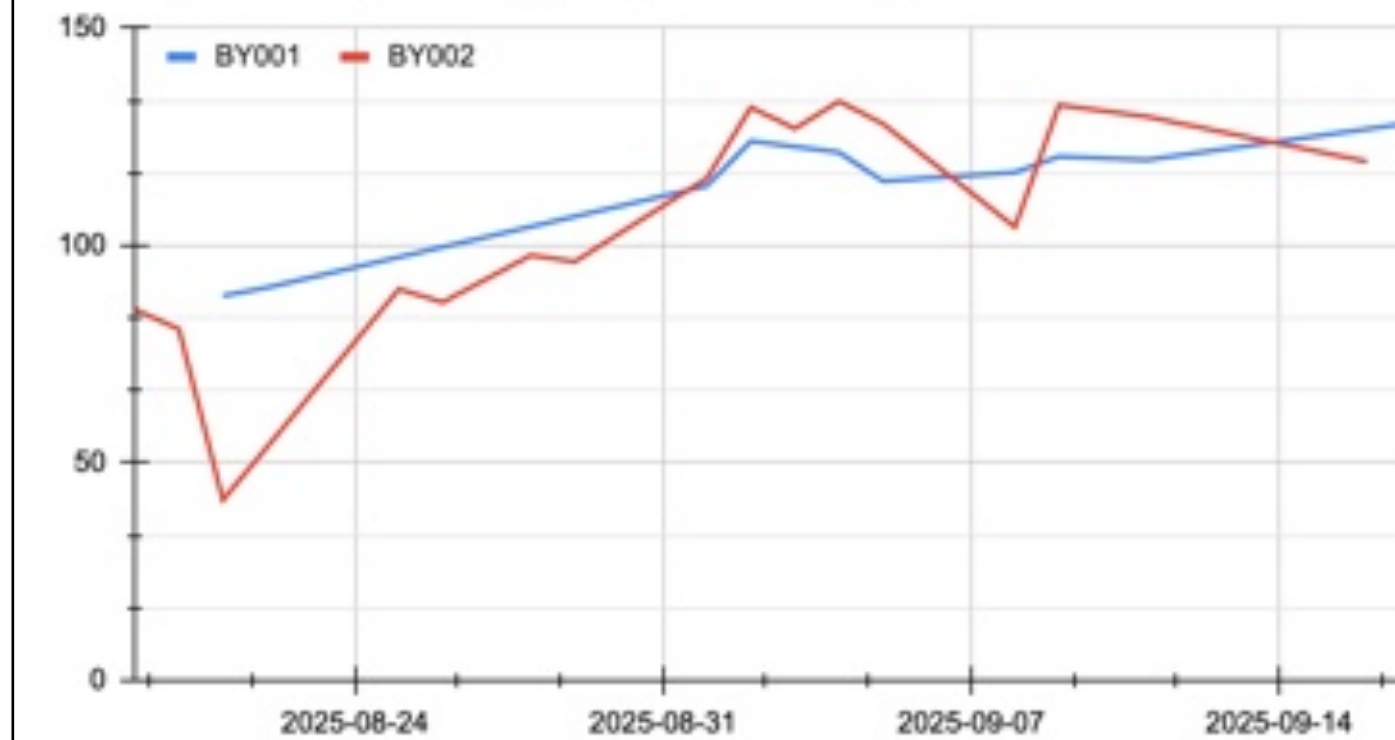
Skid Steer Operator - Wet Rental by Luminous through United Rentals

Autonomy ratio improvement over time



Autonomy as an enabler to reduce workforce labor requirements over time as the LUMI robots continuously acquire data and fine-tune its AI software to an Autonomy Ratio suitable to no longer require an onsite LUMI Engineer (Safety Operator) on premise. With software v0.1.47, LUMIs achieved on average 93.8% Autonomy Ratio. We expect to achieve over 99.99% Autonomy Ratio after "Fine-tune LUMI" (ARENA Phase II).

Hourly nameplate capacity increasing over time

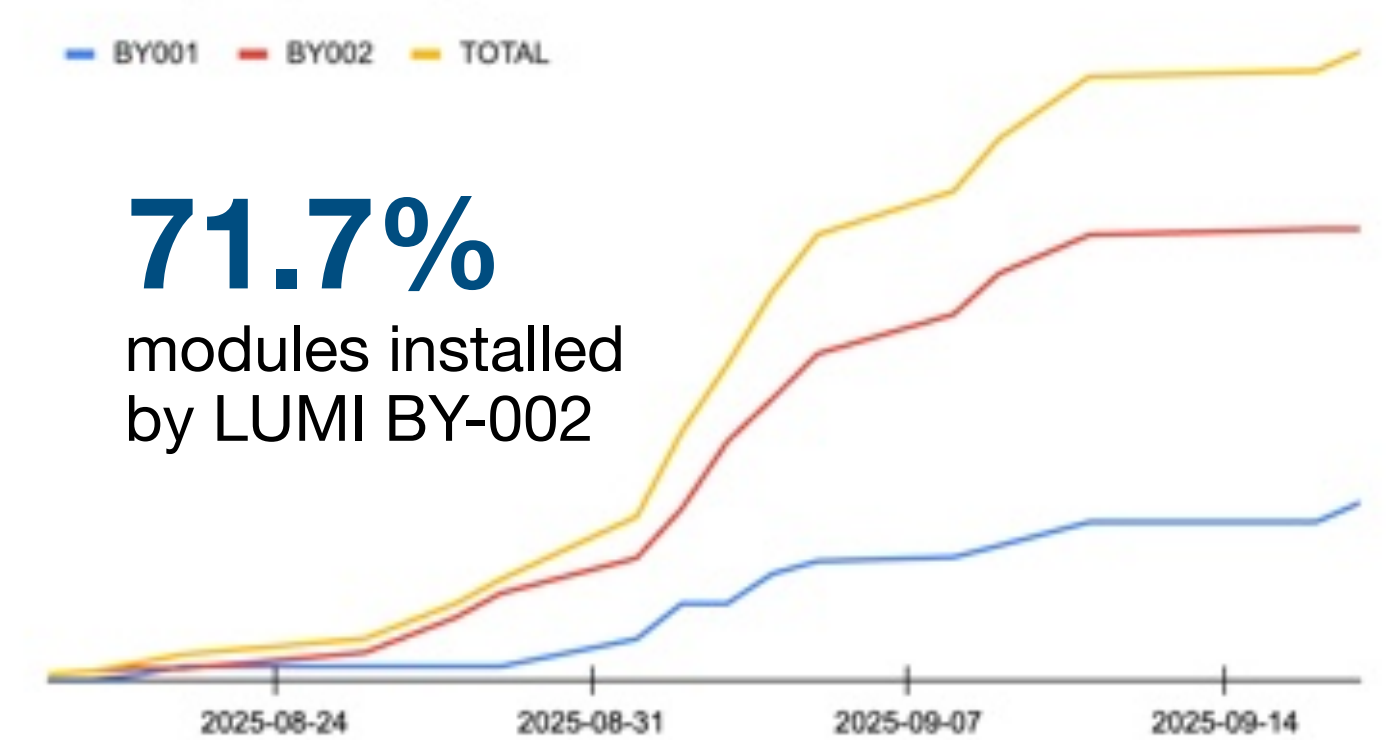


Improved nameplate capacity over time to 133 mods per hour. We noticed significant improvement as the entire crew (LUMI, skid steer operator, and laborer) learns the flow of work across shifts. The nameplate capacity is the nominal robot installation rate, without intermittent pauses or latencies (consisting of breaks, visitors, pallet recovery, etc)—this can be thought of as LUMI's peak rate.

Workforce requirement //

- 3** Workforce labor requirements per LUMI during "Pilot LUMI" (ARENA Phase I)
- 2** Workforce labor requirements per LUMI after "Fine-tune LUMI" (ARENA Phase II)
- 1** Workforce labor requirements per LUMI with advances discussed in Next Steps

Install progress by LUMIs on GESF B27 S3



71.7%
modules installed
by LUMI BY-002

Process by the LUMI fleet in completing B27 at Goorambat. To maintain flow and safety areas, BY-001 was configured to throw to the right while BY-002 was configured for left. At the beginning of the row, a 3-5 long rails exist. For nominal flow, these were skipped (not initially pre-spaced and more difficult manually) initially and were later revisited by BY-001. As a result BY-002 installed **71.7%** of all modules.



SHIFT BREAKDOWN

998 nameplate capacity

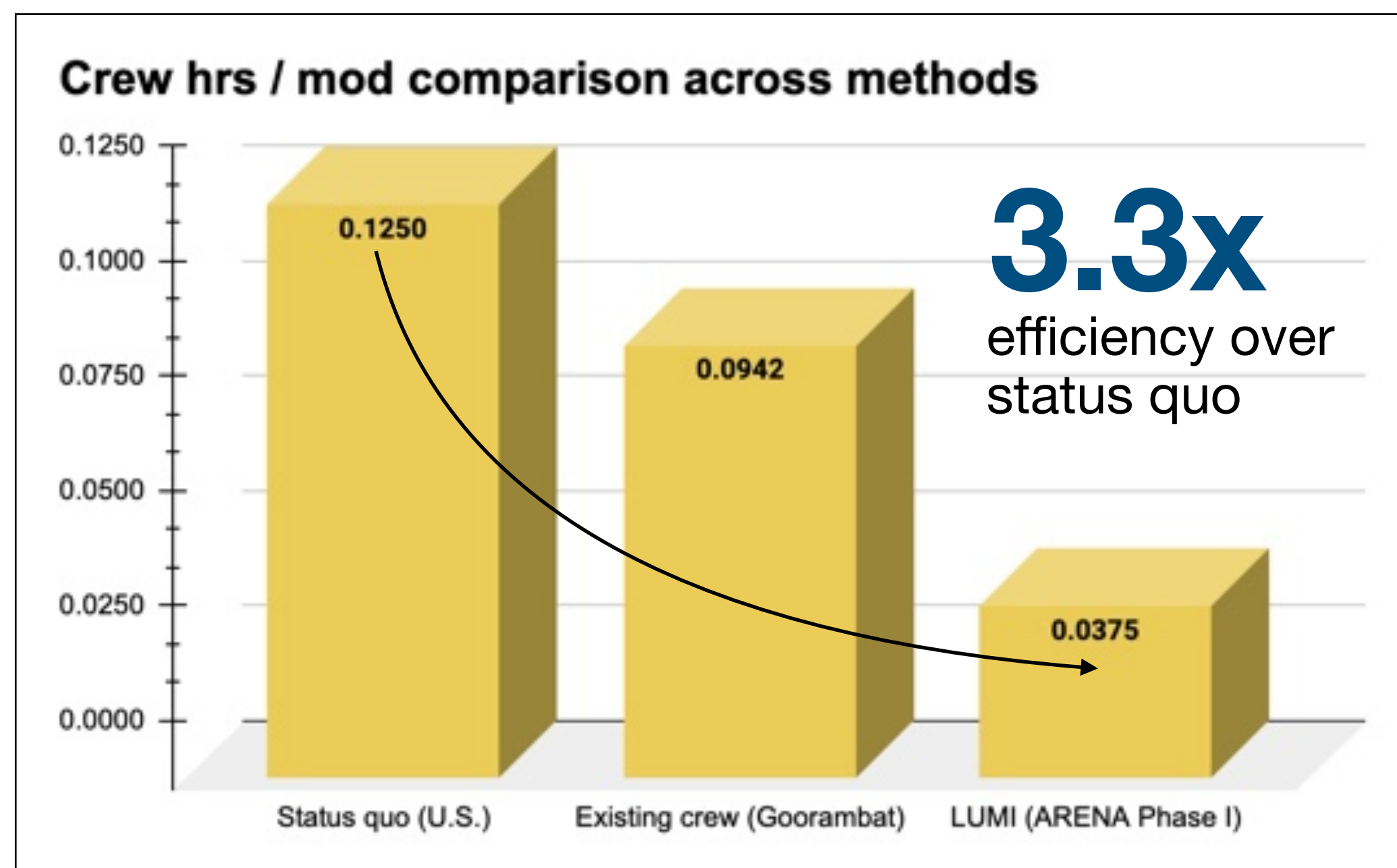
133 mod / hr (nominal)

73 mod / hr (actual)

74% operational duration

26% downtime (logistics)

58% motion duration



LUMI robots achieved a 3.3x efficiency gain over status quo.

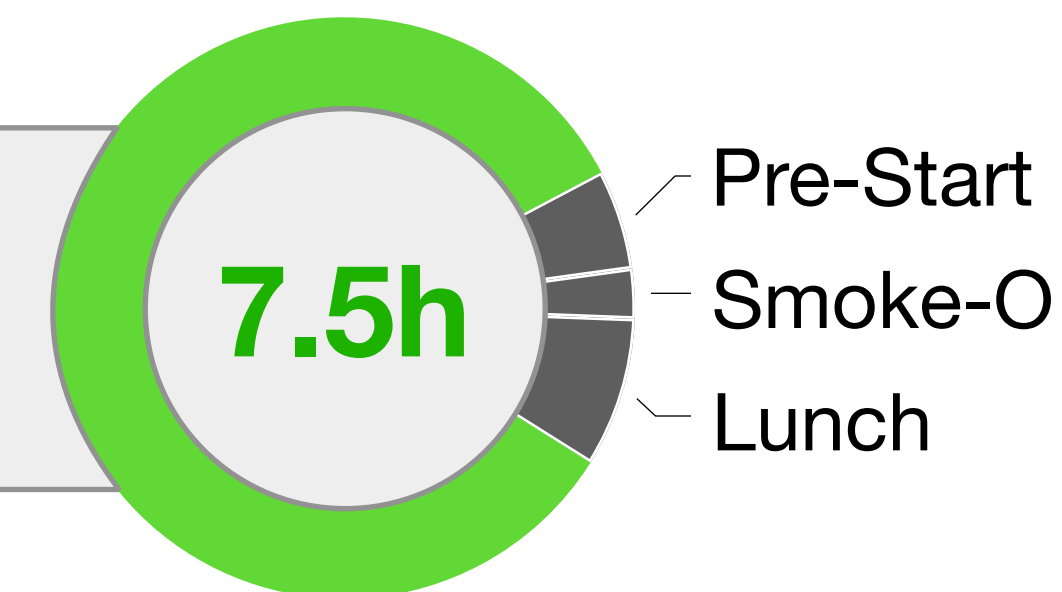
The loaded man-hours per module metric considers the entire crew's headcount multiplied by the shift hours and divides this quantity by the total modules installed during the shift. This metric accounts for the fact that increased crew sizes will naturally achieve a higher installation count at the end of shift.

While this project uses the baseline of 0.125 loaded crew man-hours per module metric for comparisons, it was found that the existing Goorambat crews were slightly more efficient, measuring at 0.0942 hrs / mod.



**PERFORMANCE
METRICS**

**Expected uptime vs.
total allocated hours**



A key learning is while the allocated shift hours is from **7am-4pm**, the expected maximum production time is about 7.5 hours. This is due to breaks for Smoke-O (a 15-min smoke break around 10am) and lunch (around 1pm) and pre-shift activities — to go over today's weather conditions, tasks, and safety information (i.e. SWMs and Take 5s). Another unintended latency is that travel time needs to be accounted for, where laborers have to walk between the crib (break area) and the work area. This can oftentimes be 100+ meters and the distance increases as more process is made, since the installed rows are closer to the crib and the unfinished work is further away. We found this, along with other miscellaneous latencies, can account for up to **26%** of loss operational duration—thus resulting in **74%** operational duration for production.

CREW RATE IS AN INTERDEPENDENT PROCESS

LUMI achieved rates where it was no longer the limiting factor. Module install is an interdependent process sensitive to the availability and work ethic of the laborers. There's a massive variance in laborers who can perform their tasks at rate—the fastest workers complete all tasks in the time it takes LUMI to place again. But to ensure all modules were secured by end of the shift, the last weeks saw the LUMIs stop production an hour earlier to provide sufficient time for the laborers to finish their tasks (full bolting, torquing and torque marking).



KEY HIGHLIGHTS & CHALLENGES



Luminous – Lessons Learnt

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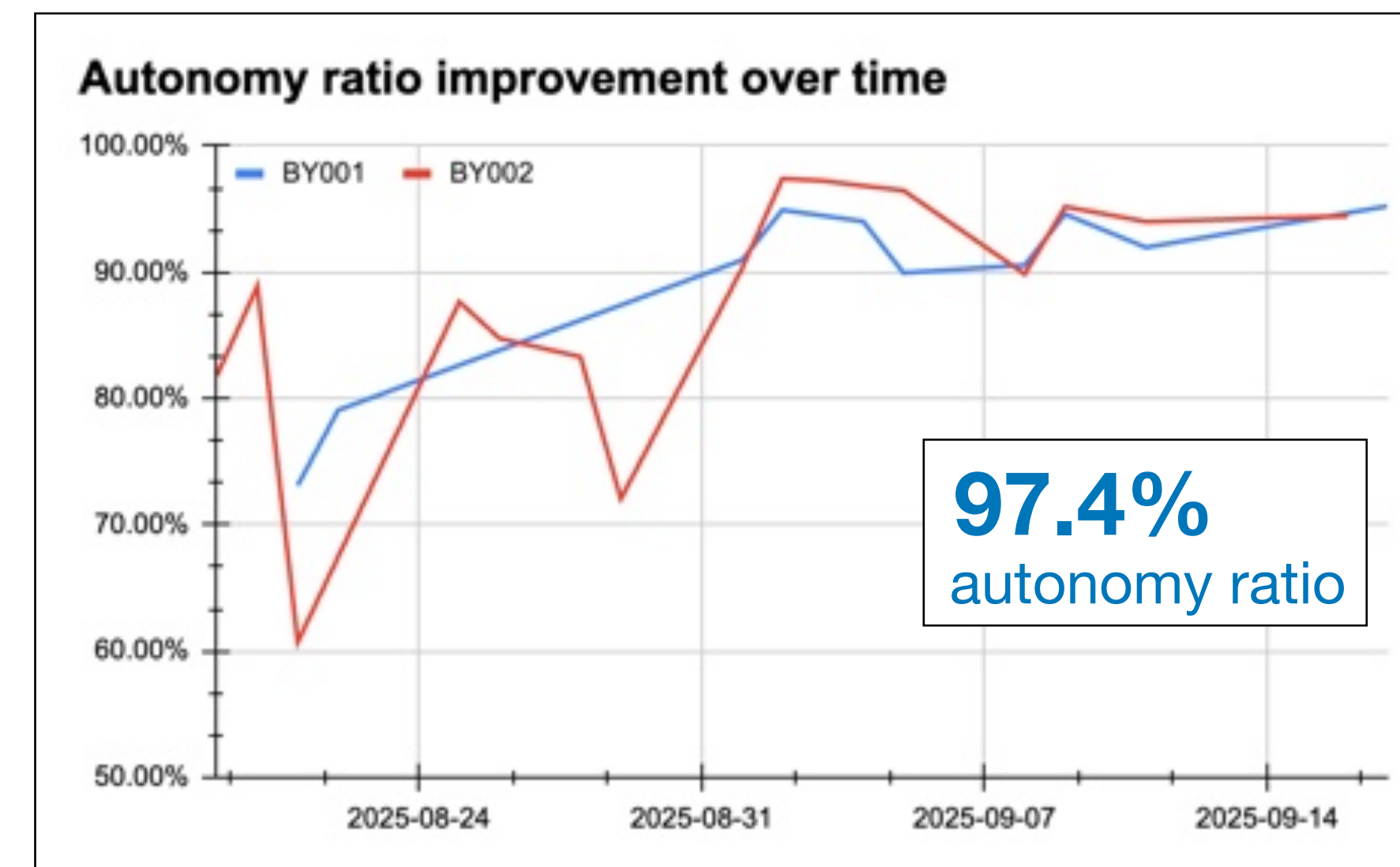
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LESSONS LEARNT (TECHNICAL)



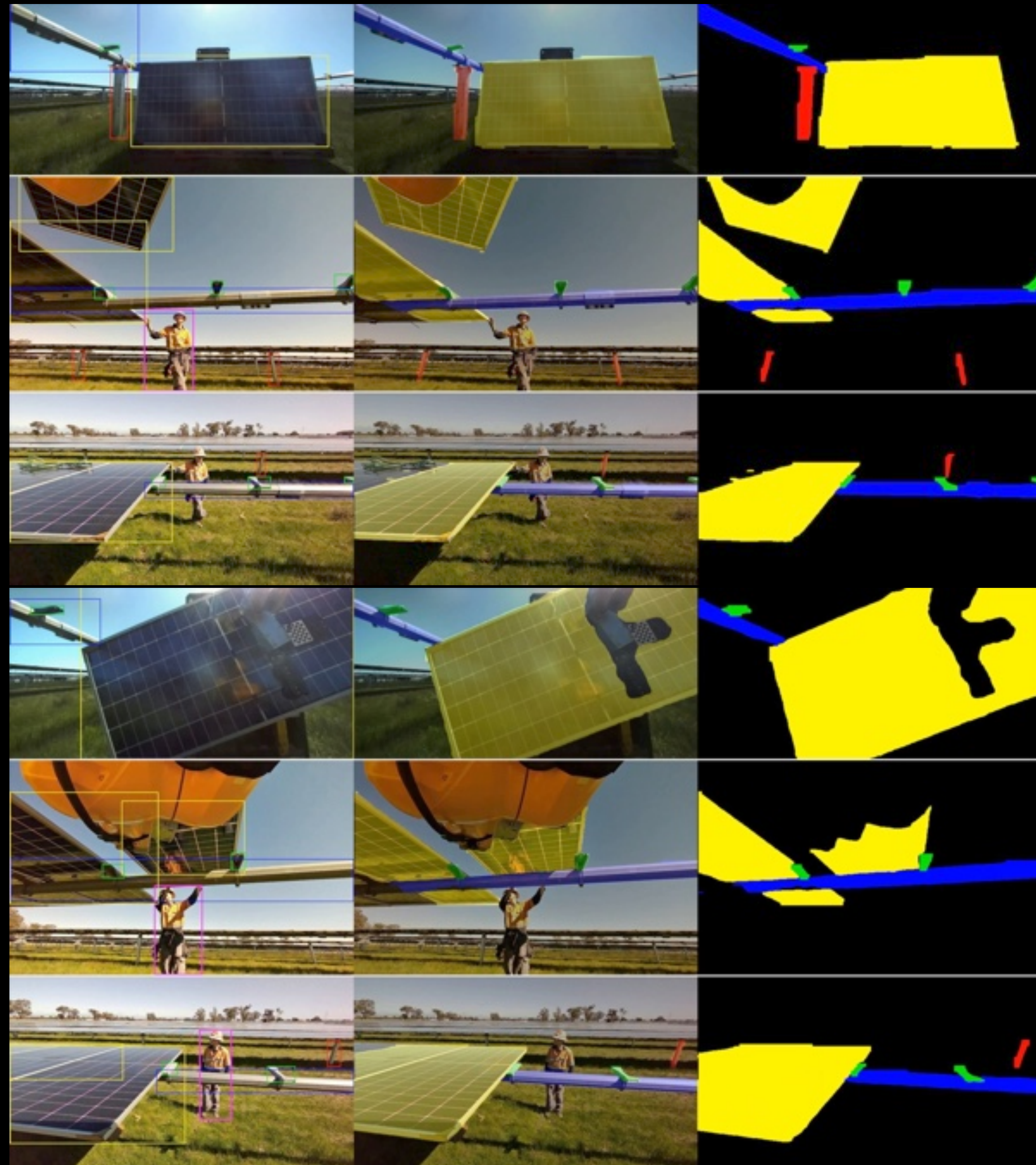
During the course of the trial, the LUMI fleet's software was **upgraded 21 times** from v0.1.27 to v0.1.47. The technical challenges addressed during these on the fly upgrades were two-fold, tackling visual nuances experienced at Goorambat and process optimizations as the fleet went from picking off staged pallets to following a skid steer down the row (to maximize installation speed and reduce vibrations on the picked modules). This was the first time the LUMI system was configured to install modules for ARRAY racking, which featured octagonal tubes and slight geometry differences at the hat rail and pile interface level. As such, the data collected played a pivotal role in fine-tuning the AI software to reliably detect and reason around the real world environment, especially with lighting artifacts and background noise.

As a result, the autonomy ratio (a metric accounting for the number of human operator interventions and confirmations against the number of total actions performed autonomously by LUMI), massively improved over time—achieving a **97.4% peak autonomy ratio**. The expectation is with Phase 2 of the ARENA project, LUMI will be continuously fine-tuned with data from both Goorambat and Culcairn.

THE CULCAIRN & GOORAMBAT SOLAR FARM DATASET

The Goorambat LUMI Series 4 fleet (serial no. BY-001 and BY-002) has been acquiring valuable onsite data instances during the full duration of the pilot program. The result is a **full audit trail** of the solar modules from its original packaging orientation inside the pallet to the placement position. Each video frame within the module installation cycle is automatically annotated and colorized by type: module, pile, torque tube, and hat rail, which are used within the LUMI workflow's reasoning software, while humans are also detected and serves as input to the safety software.

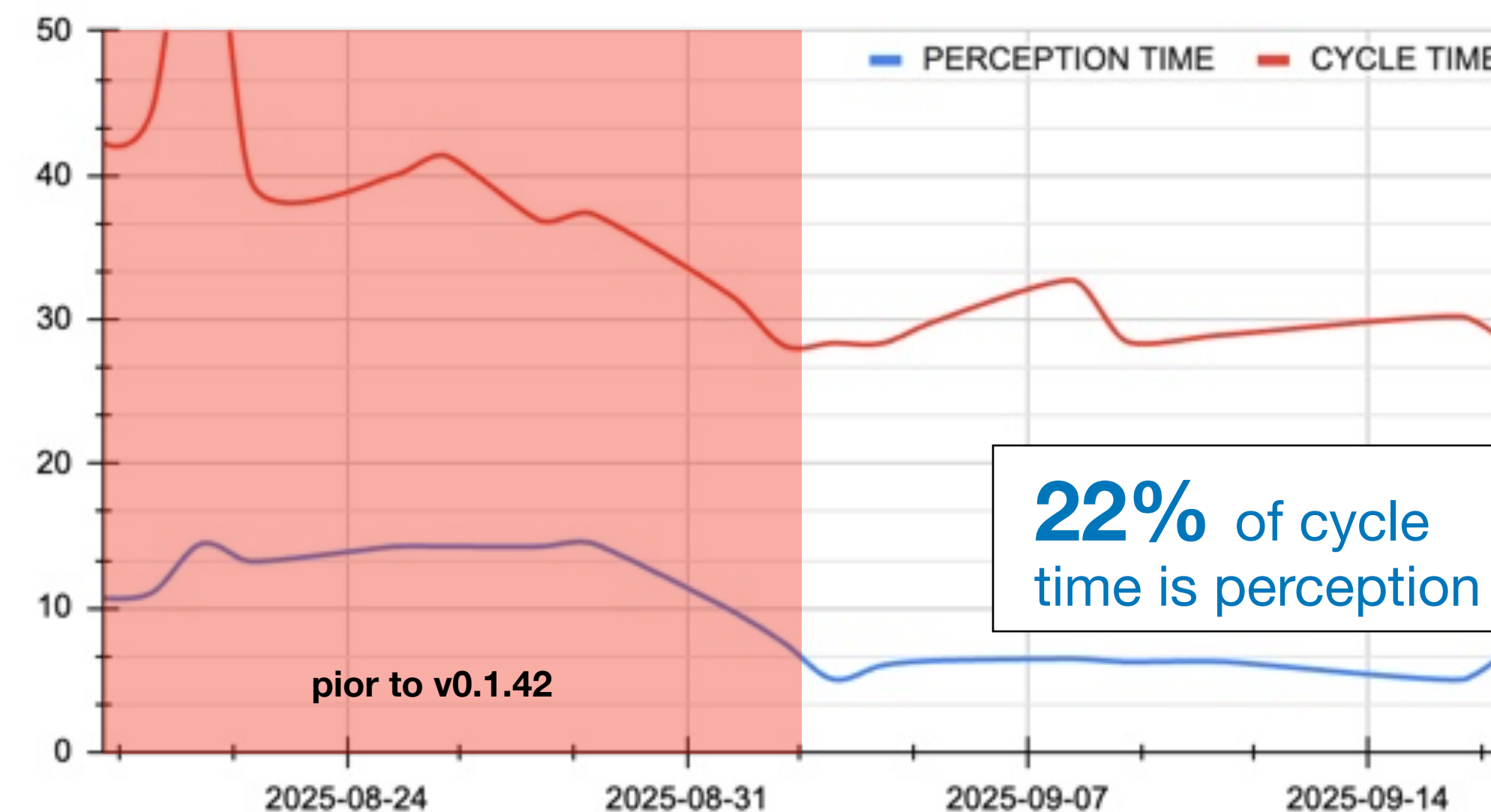
Every LUMI's data is synced up to Luminous' cloud database at the end of every shift via an onsite Starlink. Phase 2 of the ARENA project will continue to expand upon this dataset another (3) three LUMIs are deployed at Culcairn for longer durations. The intent is for us to open source this aggregated dataset, which will likely become the largest, most comprehensive solar construction dataset for robotics and AI.



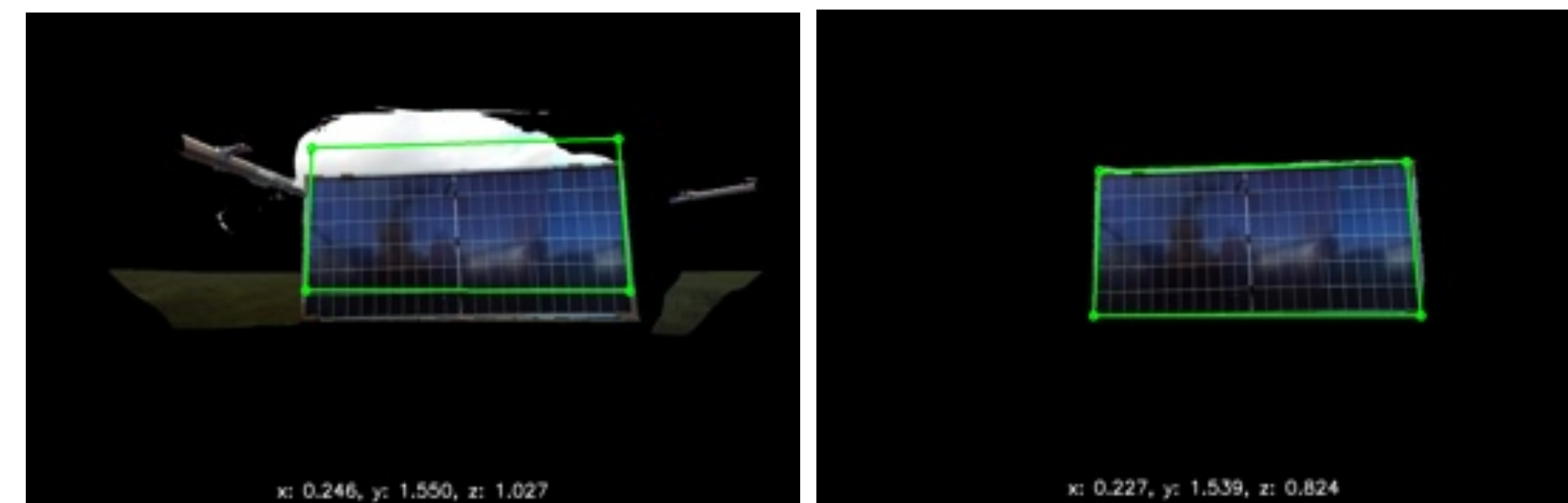


FINE-TUNING PERCEPTION WITH REAL WORLD DATA

Average module install cycle time (s) across shifts



Perception accounts for 22% of each cycle. This is the latency introduced by the robot's AI having to visualize and reason about its environment. However, by fine-tuning LUMI's AI with our newly acquired dataset, our team was able to improve reliability *and* reduce the total perception time by **55.2%** (from 14.4s to 6.3s). As a result, LUMI achieved an average end-to-end motion time of **28.6s per module**.



Prior to fine-tuning, the perception algorithms would oftentimes be confused by unexpected geometries in view. For example, the perception algorithms may output faulty results due to the background consisting of the skid steer. Fine-tuning with onsite Goorambat data enabled the software AI to become robust to such potential noise.

LESSONS LEARNT (PRODUCT DEVELOPMENT)



16 x 6 continuous improvement!

This project was the fortunate benefactor of execution across **two separately disjoint timezones**, where issues that arose in production in Australia (AEST) was immediately addressed post-shift by the U.S. engineering team (EST) overnight. This allowed for a fast iteration cycle especially around fine-tuning AI perception models, as data accumulated during the shift is used to further improve performance the next shift. The closed-loop feedback between AU and US massively enabled fast issue resolution and led to the success of this project's Phase 1.





LESSONS LEARNT (FINANCIAL)

Skid Steer & Operators. GESF had two skid steers on the entire site doing shakeout (material staging of the modules for the remaining blocks that have yet to have been installed). Therefore, it was difficult to allowed both skid steers to support the ARENA project. Instead, Luminous rented an additional skid steer and two skid steer operators (Bryce and Luke) which attributed to about an additional A\$10,000.

EL Testing. The team at GESF had some concerns with the robots causing additional micro-cracks on the solar modules during the installation process. Luminous outsourced a third party EL testing company PV Lab to perform testing on a sample of the modules installed by LUMI vs. the manual process. This compares against two types of methods for throwing modules via LUMI:

(A) where LUMI picked off staged pallets and traversed up to 20 meters—for more details see Lessons Learnt (Process).

(B) where LUMI pick off a skid steer and immediately installed panels onto the racking, eliminating addition movement and vibrations to the module during the installation process.

LESSONS LEARNT (ENVIRONMENTAL)

Our team came across various environmental situations and unexpected events, some caused the entire site to shutdown while others have periodic downtime. These instances dramatically impact the operational times for the robots and as a result, the realize number of modules installed within the shift.

Meanwhile, there's a number of health and safety considerations when working on the construction site. Weather conditions revolving around dust, wind, and rainfall may also create situations where it is either unsafe to work or the impact of bogged vehicles may cause more damage to the site than time saved working during such conditions. We've noticed a number of times the site was called off due to rain.

In addition, GESF site induction has done a great job informing our staff regarding various wildlife on site - from insects within the boxes to snakes and kangaroos that were onsite at various times. It's important to always wear PPE and be aware of one's surroundings at all times when actively on the site.



Wind - Persistent high velocity winds of over 35 km/h will result in stoppage for module installation as it becomes dangerous for workers.



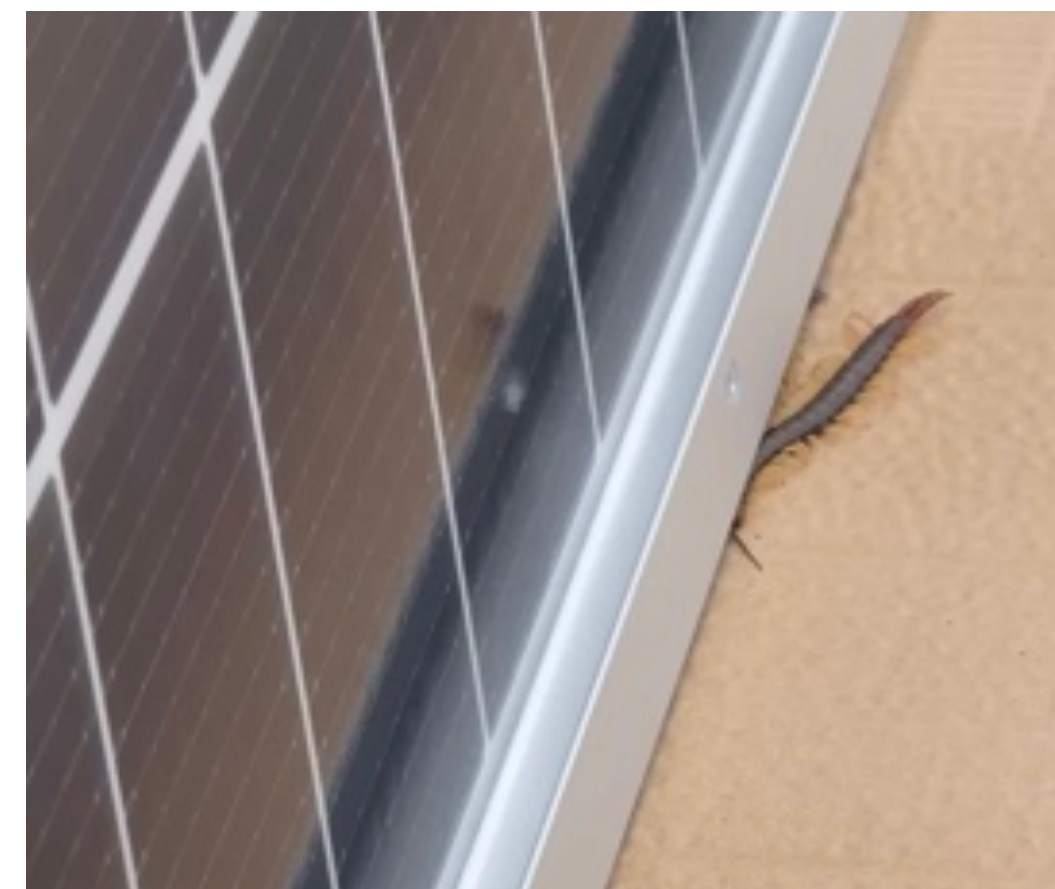
Thunderstorms - Major safety issue. We witnessed "red alert" meaning a storm was in proximity and we had to immediately stop work and go to the main crib.



Mud - Another source of stoppage is when the ground conditions sufficiently muddy that the equipment needs to terminate work, minimizing damage to the site when vehicles get bogged.



Dust Control - periodically trucks will spray water to make airborne dust heavy enough to prevent it from becoming hazardous to workers' health



Wildlife - Centipedes and ants may be present inside boxes as well as wild animals like kangaroos and snakes on the construction site. Always wear appropriate PPE and be aware of when working.



Rubbish - At the end of the shift, rubbish consisting of cardboard, plastic, and straps from the box of panels are sorted and then placed into the correct rubbish containers to be disposed of and recycled.



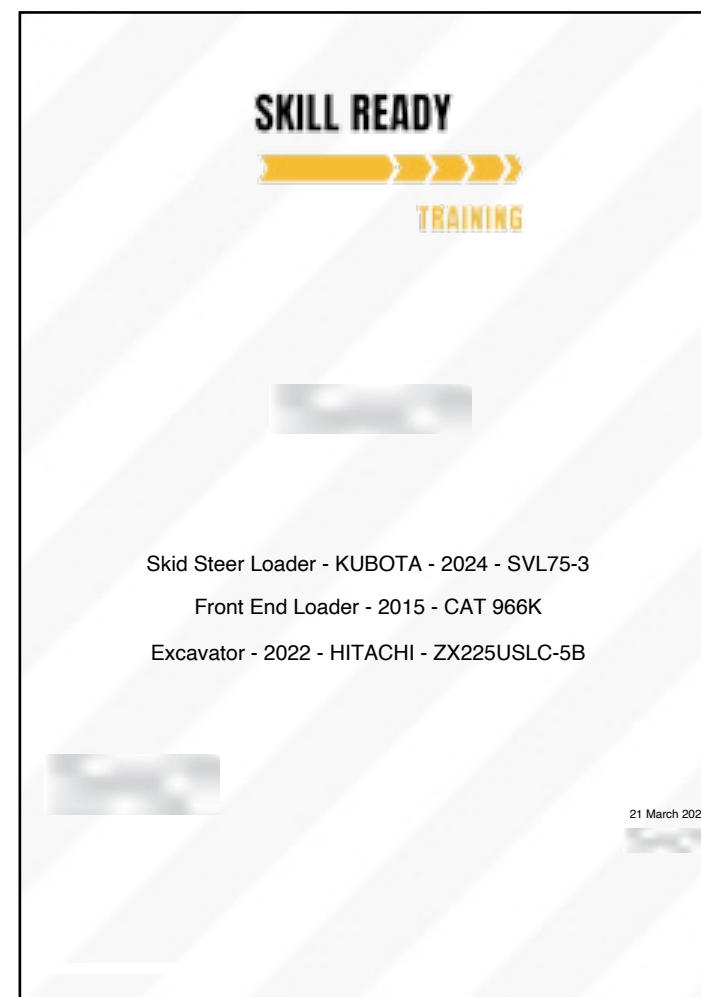
LESSONS LEARNT (REGULATORY)



Example of construction induction and site induction cards required for this project.

SAFETY ESSENTIALS. Every Luminous onsite technician (and Engineer) was required to complete the in-person “white card” training (Construction Induction) for the state of Victoria (CPCWHS1001 - prepare to work safely in the construction industry), by WorkSafe VIC. Then, we had to be separately site inducted through an onsite orientation process managed by Equans. All materials (including white card, passports, and work visas) had to be uploaded to 3DSafety (the onsite safety software at Goorambat) to be site inducted.

3DSafety - At the beginning of the shift, every construction staff had to sign in using their GESF cards and pass the onsite breathalyzer located at the main crib area. They’re then officially signed into the solar farm system and can attend pre-start before getting transported to their denoted work areas.



Certifications of Competency - All onsite construction equipment operators must have a form of verification stating they have been properly trained for the specific piece of equipment. This includes the skid steers, pile drivers, excavators, and even the LUMI robots. Luminous has trained our own engineers and technicians to operate the robots and provided them all with completed and approved certifications.

LESSONS LEARNT (SAFETY)

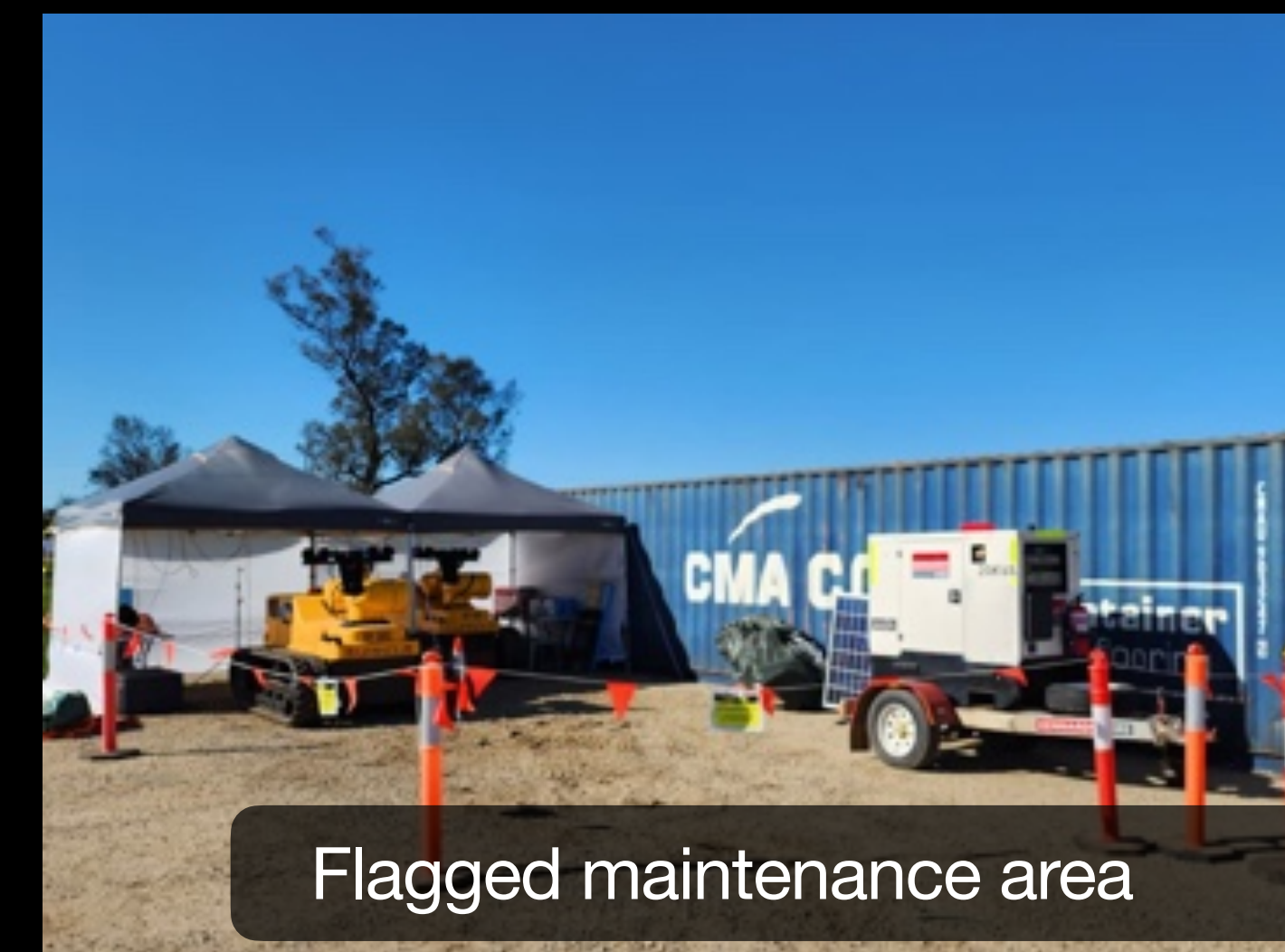
Our team is proud to announce that during the entire course of module installation production with the LUMI robot fleet at GESF, **zero safety incidents** were reported.

The safety team from Goorambat and Luminous meticulously drafted and continuously updated the Safe Work Method Statement (SWMS) to ensure that all workers were knowledgeable to safely conduct high-risk construction work. The SWMS identified potential hazards, assessed risks, and detailed the control measures to be used to mitigate each of those risks—most of these were consistent with the construction equipment like Bobcats and excavators.

An additional safety measure was taken by creating **flagged work areas** where only LUMI robots, trained operators, and Bobcats were able to access. We designed the workflow such that each robot would throw modules to the left and right, inwards to the construction crew, with the robots in the outside flagged rows.

Furthermore, operating in **high wind conditions** is especially dangerous. As such, the wind speeds were constantly measured throughout the shift, at instances where persistent speeds were over 35 km/h, production would be paused temporarily. This is an example where safe work conditions creates a bottleneck to the human work process. At the limit, we believe as we scale machinery and robotics to tackle more of the dangerous work conditions, we may eventually no longer be constrained by these types of safety induced constraints for humans and truly build solar farms at the machine's nameplate capacity.

0 safety incidents



Flagged maintenance area



Flagged work/production area



LESSONS LEARNT
(LOGISTICS)

Bill of Lading	Status	Last Event	Transport Mode	Container Mode	Consignee	Destination
504778874	In Transit	Booking confirmed, 9/20/2025	Sea	LCL	LUMINOUS ROBOTICS PTY LTD	MELBOURNE AIRPORT
504755649	Delivered	Delivered at MELBOURNE AIRPORT, 8/12/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	MELBOURNE AIRPORT
504740403	Delivered	Import customs cleared, 8/4/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	MELBOURNE
504732715	Delivered	Delivered at BOSTON, 7/25/2025	Air	LSE	LUMINOUS ROBOTICS C/O MASSROBOTICS	BOSTON
504731724	Delivered	Delivered at MELBOURNE AIRPORT, 7/25/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	MELBOURNE AIRPORT
504727362	Delivered	Import customs cleared, 7/21/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	SYDNEY
504724397	Delivered	Import customs cleared, 7/17/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	SYDNEY
504718579	Delivered	Delivered at MELBOURNE AIRPORT, 7/16/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	MELBOURNE AIRPORT
504716043	Delivered	Delivered at MELBOURNE AIRPORT, 8/13/2025	Sea	FCL	LUMINOUS ROBOTICS PTY LTD	MELBOURNE AIRPORT
504700489	Delivered	Delivered at BOSTON, 7/12/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	BOSTON
504690554	Delivered	Import customs cleared, 6/19/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	MELBOURNE
504687468	Delivered	Import customs cleared, 6/19/2025	Air	LSE	LUMINOUS ROBOTICS PTY LTD	MELBOURNE

Our team along with our partner, Rohlig, has learned significant lessons around export and import between U.S. and Australia, both for our components as well as our vendors’. Of these freight shipments, **91% were by air** due to the compressed timeline for us to manufacture, assemble, transport, and deploy onsite at Goorambat.

Shipping by air is 5x more costly than by sea!

LOGISTICS BY THE NUMBERS //



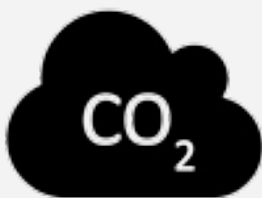
11
shipments



11,291
kg transported



168,553
km traveled



48.504
tons of CO2 emissions

LESSONS LEARNT (PROCESS)

Robot motion
accounts for
60% of cycle.

Process
accounts for
40% of cycle.

Process flow is a major driver of performance rate.

LUMI is a system must work intimately as part of an overall process that consists of manual workers. Therefore, the flow of work massively impacts the performance of the robot and how it interfaces as part of the holistic cycle and rate of installation. This pilot featured two different flows of work which provided our team with key lessons and insights. Fortunately, LUMI has been designed with the objective of risk mitigation and ability to conform to any construction site's unique flow. As such, the configuration between these methods have been extremely seamless.



Staged pallets. Manual workers unbox the pallet and then lean them against rigs at a slight angle to prevent them from toppling over. LUMI interfaces to this type of panel presentation by driving to and from the staged pallet to the place location. All motions are planned relative to the perceived productions being manipulated. The pallets at Goorambat has been pre-staged to support this workflow at approximately the nominal distances assuming two LUMIs (see next page).

Pros: No additional manpower or equipment

Cons: Added latency for driving to/from pallet
Added vibrations to the panel during travel



Skid steer following. Manual workers prematurely unbox pallets downstream the row which is then picked up by a skid steer to the place location. Both LUMI and the skid steer jointly traverse down the row one module distance at a time. LUMI picks the module off the skid steer and immediately places it onto the racking to the side of the robot. Nominally, the flow of work has one row where humans operate and LUMIs to the left and right throwing inward.

Pros: No latencies or vibrations to panel after pick

Cons: Additional machinery needed (skid steer)
Added operator and additional complexities
coordinating machinery + laborers

LESSONS LEARNT (PROCESS)



Process optimization involves GEOMETRY optimization.

While there were a number of important process optimizations that enabled faster rates as the project went on (including the orchestration of laborers and understanding the sequence of tasks they perform and when), it turns out, geometry optimization is an extremely impactful variable to consider.

Pallets were **initially pre-staged based** on a workflow that required the robots to pick a panel and travel up to 20 meters. This added additional latency. Later, the workflow was updated to follow skid steers (Bobcats) that would travel down the row leading the LUMI robots. Because the site was already pre-staged where every other row was empty, the flow had to conform to the layout geometry, which meant that the robots (and skid steer) would travel down the empty rows with humans being in the rows that had the staged pallets, localizing the work by humans to a single row. Further, this allows laborers to safely pre-open the pallets as well without having to enter into the robot workspace.

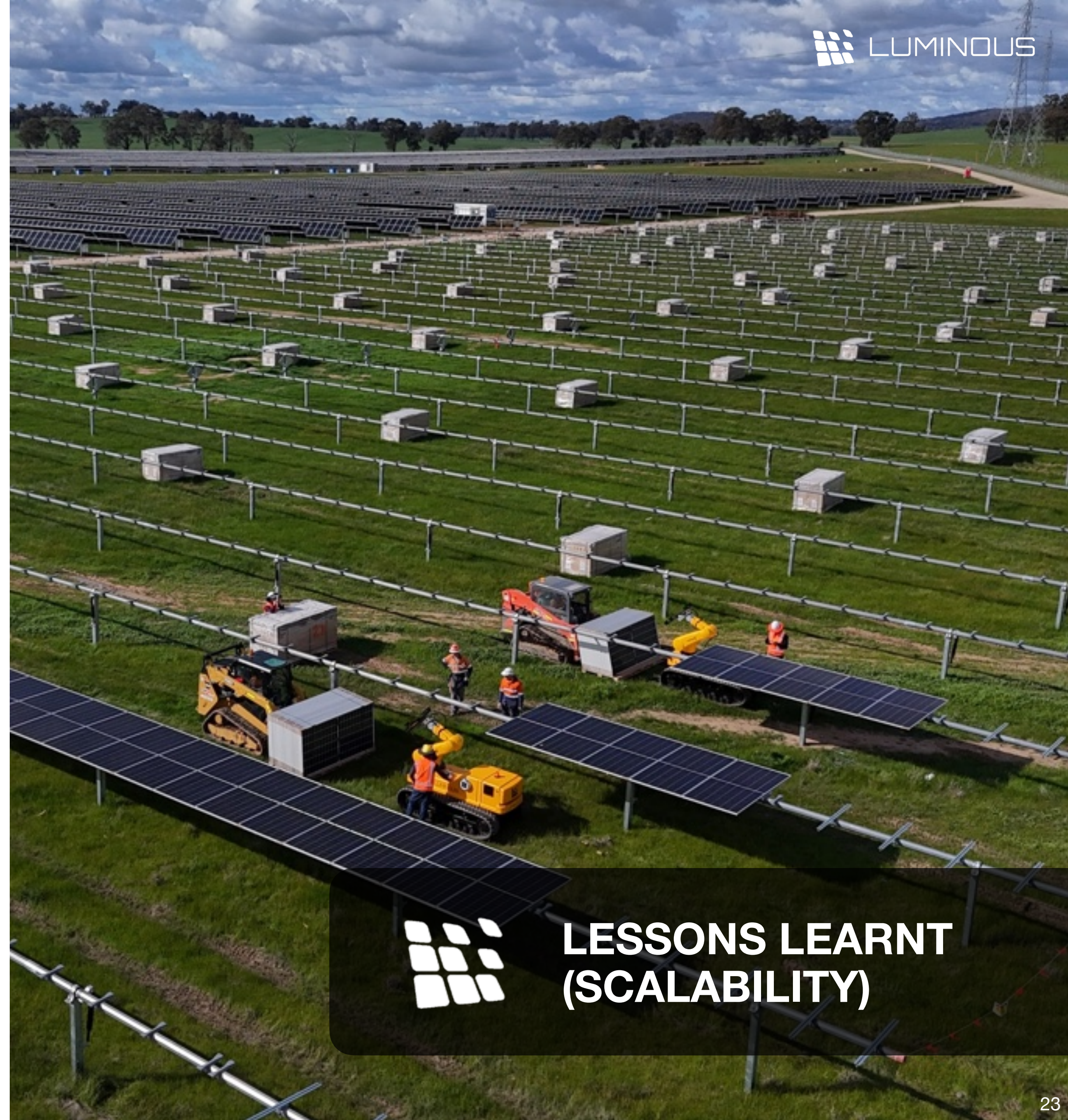
We eventually learned that **this staging was sub-optimal**, because the skid steer would have to traverse the row and “exit”, then enter the row next to it to retrieve new pallets. Doing so, added an additional 5-10 minutes per box. This also create a scaling issue since the faster the LUMI robots depleted the pallets, the more added latency there was to retrieve new pallets by the Bobcats. Near the end of the project, we altered the staging to be clustered near the end of the rows, which reduced the travel distance for the Bobcats, since they only had to travel to a row’s distance and back. This brought the **pallet retrieval time to about 2 minutes** per box.

The most important insight we've learnt is that module install automation is a holistic, cohesive optimization problem that is beyond just building a shipping a fleet of robots. The longer term opportunity sees Luminous as a bespoke lean process specialist that considers fine-tuning the overall installation process.

Effective **coordination of pallet staging and unpacking** is critical to minimize robot downtime. Since this process relies on the same pool of labor used for other tasks, both resource allocation and task timing need to be carefully managed as operations continue to scale further.

The pallet delivery problem to LUMI is also to consider at scale as logistics constituted for **26% of the overall shift** time (i.e. the times it took the Bobcat to retrieve a new pallet and return).

At scale, we envision a fleet of LUMI manipulator robots and logistics robots, where the panel installation flow does not stop since a new box is immediately ready the moment the previous box has been depleted. Doing so, converges the rates of this distributed fleet based solution towards what fixed automation solutions can achieve—without the process and integration risks that they carry.



**LESSONS LEARNT
(SCALABILITY)**



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