Digital Twin Enhancement for Sustainability

A Belimo White Paper

Prepared in collaborative spirit and effort with

HY THINK HY PERFORMANCE beecon

BELIMO®

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Digital Twin Enhancement for Sustainability: A Belimo White Paper

Leveraging Technology for a Sustainable Future:
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Digital Twins are a set of digital tools that Industry 4.0 has identified to improve many industrial processes and targets. With the rapid advancement of AI and IoT, Digital Twins are expected to become a standard in the Industry. However, this widespread adoption resulted in varying standards and definitions. In this White Paper, HY will present a White Paper for Belimo India Automation Pte Ltd on how a Digital Twin helped them achieve higher sustainability standards and estimate the impact of building expansion.

1. Introduction

Belimo India Automation Pte Ltd is a global leader in developing, producing, and marketing innovative actuator solutions that promote sustainability and energy efficiency in heating, ventilation, and air conditioning (HVAC) systems. With a strong commitment to improving comfort, safety, and energy management in buildings, Belimo uses advanced technology to enhance performance while significantly reducing environmental impact. As a subsidiary of the Switzerland-based Belimo Group, the company combines global expertise with local knowledge, providing customized solutions for the varied needs of the Indian market.

Sustainability lies at the core of Belimo's mission. Recognizing the urgent need to address climate change and resource scarcity, the company has set ambitious goals to improve energy efficiency and cut greenhouse gas emissions across its operations and solutions. Belimo India aims to help buildings achieve net-zero energy consumption and significantly contribute to global decarbonization efforts by focusing on high-performance actuators, energy-efficient HVAC components, and IoT-enabled devices. This commitment aligns perfectly with India's sustainable development agenda and global climate objectives.

Belimo India's strong focus on sustainability has resulted in the adoption of Digital Twin technology to optimize the energy performance of its Belimo CESIM house. By creating a virtual replica of the facility, the company aims to simulate, monitor, and analyze real-time building performance, allowing it to recommend energy saving measures that enhance efficiency and reduce waste. This innovative approach highlights its commitment of using advanced technology for greener building solutions.

As energy consumption in commercial facilities keep increasing, traditional HVAC and energy monitoring methods often fail in addressing changing performance needs, system integration issues, and predictive energy efficiency plans. Belimo aims to solve these problems with a Digital Twin that can benchmark current performance and also simulate potential scenarios like building expansion, retrofits, and solar installations.

Beyond product innovation and digital transformation, Belimo India actively engages in partnerships, education, and outreach to promote sustainable practices within the

HVAC industry. By encouraging collaboration with industry stakeholders and supporting green building initiatives aligned with the group vision of “Together to the top,” Belimo ensures its influence extends beyond its operations, creating a ripple effect that promotes sustainable change throughout the built environment. Through these efforts, Belimo India emphasizes its vision of a greener, more energy-efficient future for buildings across the country and beyond.

2. Digital Twin Implementation at Belimo CESIM House

The Belimo CESIM House, in Rabale, Navi Mumbai, is a state-of-the-art IGBC Platinum-rated industrial facility—one of the highest certifications achievable for sustainable manufacturing buildings in India. Designed as a smart factory and experience center, the facility covers an area of **7,782 m²**,including built-up spaces, parking, driveways, and basements, with **3,800 m²** designated as Gross Floor Area. It combines logistics, shopfloor operations, technical support, and a dedicated classroom for HVAC and automation industry stakeholders. In 2023 alone, the facility hosted over **1,100 visitors**, including consultants, contractors, and industry professionals—demonstrating strong market interest in its advanced sustainability features and Belimo’s leadership in next-generation HVAC technologies. The building achieved an impressive **Energy Use Intensity (EUI) of 33.74 kBTU/sqft/year**, well below the regional benchmark of **65–80 kBTU/sqft/year** for similar tropical-climate industrial facilities, placing it among the most energy-efficient factory buildings in the country.

The Belimo CESIM House demonstrates Belimo’s commitment to sustainability, focusing on its purpose: **Comfort, Energy Efficiency, Safety, Installation ease, and Maintenance** (CESIM) operations with an additional 5-year warranty on the systems. At the core of Belimo, there is a dedication to prioritizing environmental factors at the heart of their business values. Specifically, Belimo emphasizes two Sustainable Development Goals:

1) **Good Health and well-being**: Belimo develops products that provide high indoor air quality for occupant’s comfort and critical applications
2) **Climate Action**: Belimo’s products are meant to save energy and reduce CO2 emissions.

As seen in Fig. 1 below, Belimo applies these two SDGs as shown. This demonstrates Belimo puts a strong focus on client and customer needs.

Figure 1 Belimo's SDG application to Comfort, Energy, and Safety. The three main areas of focus that are pertinent to clients and customers.

At the core of CESIM House's energy performance are Belimo's high-efficiency HVAC field devices. The facility is features:

- **Energy Valves** that combine flow measurement, pressure-independent control, and delta-T Management
- **Smart actuators and sensors** that regulate temperature, humidity, and CO_2 at the zone level
- **IoT-enabled meters** that feed real-time data to the BMS

Together, these components adapt HVAC loads dynamically based on occupancy and climate conditions, minimizing energy use without sacrificing thermal comfort.

Key HVAC infrastructure includes:

- **AHRI-certified high COP water-cooled screw chillers**
- **Twin cooling tower system**
- **Fixed primary and variable secondary pumping**
- **Smart AHUs** with heat recovery wheels
- **EC fans** and **Variable Frequency Drives (VFDs)**

These design and operational measures resulted in:

- **25–35% HVAC energy savings** vs. conventional baselines
- **Predicted overall building energy savings of 23%**
- **Over 30% of total energy load supplied by solar PV (100 kW capacity)** from 186 rooftop panels

The outcomes of these design and operational measures resulted in **95% of regularly occupied spaces** receiving daylight and exterior views, with ventilation rates that exceeded IGBC norms by **30% higher CFM**.

Additionally, CESIM uses MERV-8, MERV-13, and electrostatic filters to ensure high indoor air quality, maintain thermal comfort as per **ASHRAE Standard 55-2020,** and reduce waste by using **E-paper displays** that provide real-time IAQ feedback.

In 2023, Belimo partnered with HY to develop a Digital Twin model and an accompanying dashboard to **validate current achievements,** improve the sustainability of the Belimo CESIM House and lower its indirect carbon emissions by identifying additional savings.

This case study illustrates how HY's 3-Phase framework was implemented at the Belimo CESIM House, highlighting the structured methodology and its resulting benefits.

HY's proposed 3-Phase framework is seen below in Figure 2.

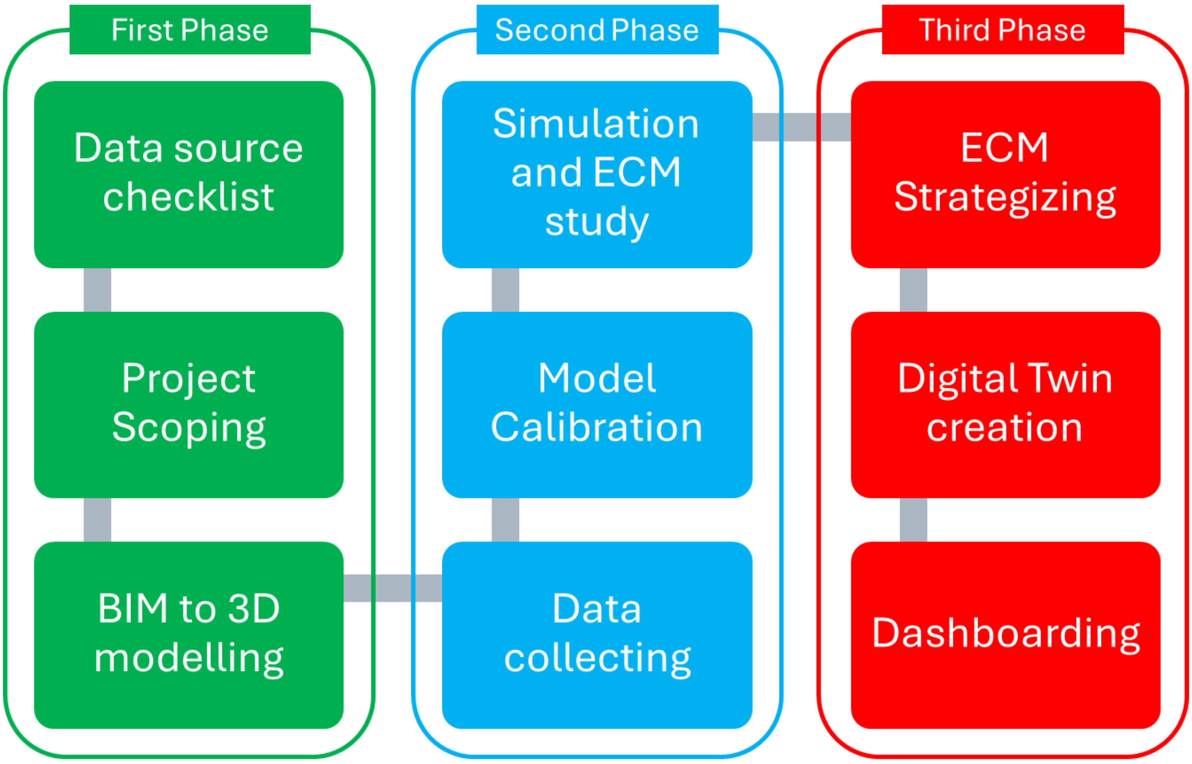

Figure 2 HY proposed 3-Phase Digital Twin Project Flow Framework

This white paper is organized according to the 3-Phase framework and will guide the reader through the project's flow.

2.1 First Phase: Boundary and Foundation Setting

The initial phase focused on laying a solid foundation for the Digital Twin project. The critical activities included:

2.1.1 Data Source Checklist

For the pre-project phase, Belimo filled the comprehensive data source checklist as shown below. The checklist was split into three categories: Fixed Parameters, Dynamic Parameters and Measured Calibration. Each category represented a different type of data relevant for the development of a Digital Twin.

Fixed parameters focus on the static design and equipment specifications of the building and its systems. It includes architectural layouts, HVAC design schematics, and lighting infrastructure essential for baseline energy modeling.

Dynamics parameters capture operational profiles and control strategies that vary with occupancy or usage. It includes setpoints, sensor configurations, and schedules for lighting, equipment, and HVAC operation.

Finally, measured calibration parameters focus on actual measured data from the building's systems to validate simulation accuracy. This includes utility consumption, chiller plant performance, and sensor-based monitoring records over time.

For the full list, please refer to section Appendix A.

2.1.2 Project Scoping

As mentioned in the introduction, Belimo requested a Digital Twin with a Dashboard to help improve the sustainability of the Belimo CESIM building, keeping true to their core business values. To that effect, Belimo requested the Digital Twin and dashboard to cover the following:

1. Enhance Energy Efficiency
2. Identify sources of energy wastage
3. Reduce overall energy consumption
4. Inform the strategy to bring Belimo CESIM towards Net-Zero or even Zero-Carbon.
5. Energy conservation measures recommendations
6. Estimate impact on existing chiller systems with the addition of several new floors.

The dashboard accompanying the Digital Twin would indicate key metrics for the Belimo management team for monitoring their targets.

2.1.3 BIM – to – 3D

With the comprehensive files provided by Belimo, HY was able to convert the BIM files into high-fidelity 3D models. Key components, such as thermal zoning, HVAC systems, lighting points, IoT sensor placements, and material properties, were accurately represented.

With the ample data files and information provided, HY was able to create accurate 3D models as seen in Figures 3 – 4 below. In Figure 3, the Axonometric view provides a bird's eye view of the Belimo CESIM building and the surrounding buildings. This provides viewers with an understanding about the potential effects of shading.

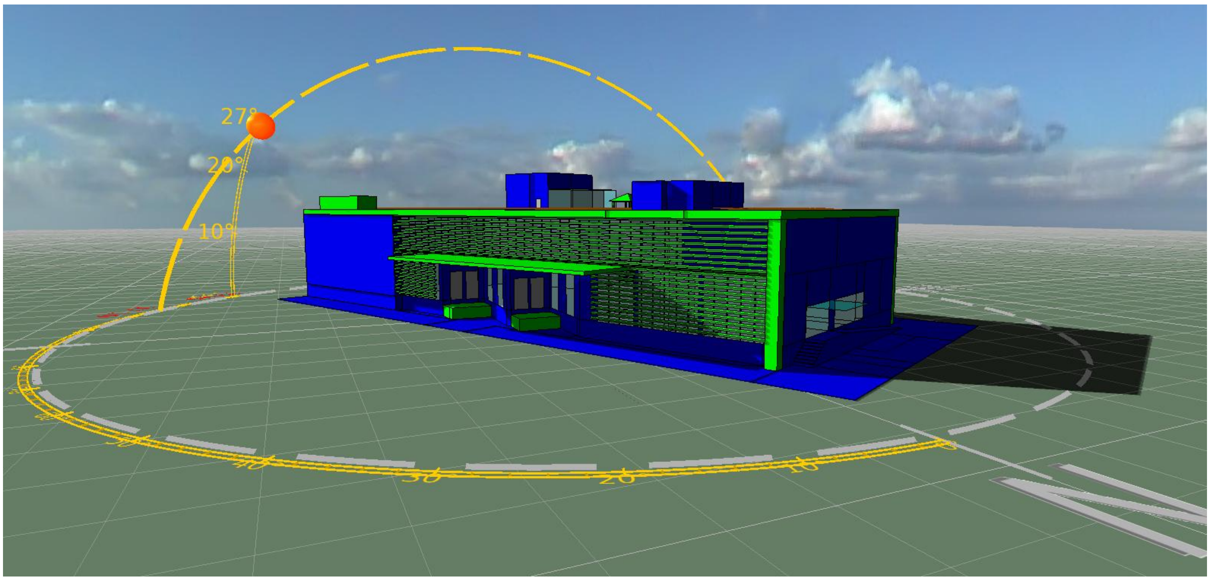

Figure 3 CESIM 3D and Solar Insolation View.

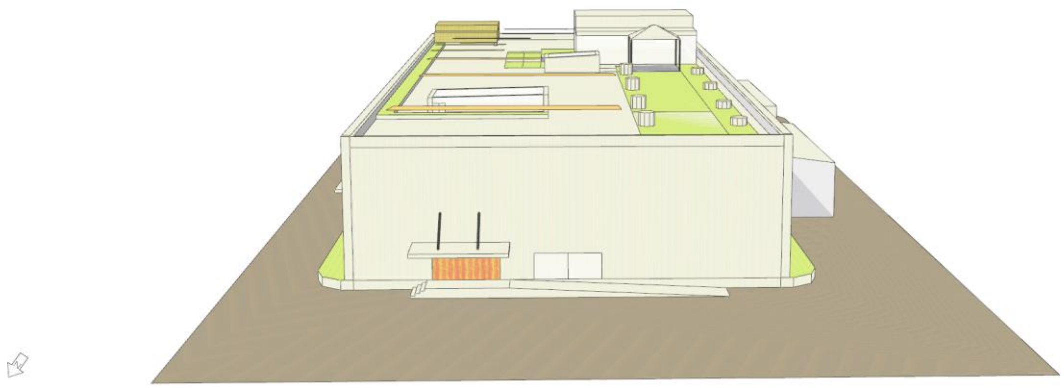

Figure 4 CESIM North Elevation

As seen from the figures above, the provided data files allowed the creation of extremely high-fidelity files. Also as seen from the Axonometric view in Figure 3, the surrounding environment's buildings are also included in the 3D model. This is crucial for the solar insulation simulations further adding accuracy to the calibration in the later steps.

2.1.4 Current-State Performance Summary

Prior to Digital Twin deployment, the building's key operational parameters were benchmarked. Notable baseline includes:

kW per RT for the chiller plant	0.6544 kW/RT at maximum load
Solar generation	10MWh average monthly
Cooling load distribution across zones	
Energy bills	

Table 1 Current-State Performance Data of Belimo CESIM that can be shared

For privacy reasons, some data will not be fully displayed. This data served as the foundation for model calibration, impact assessment, and scenario simulations.

2.2 Second Phase: Modelling, Simulation, and Analysis

2.2.1 Data Collection

Operational data was collected over 12 months. However, because Belimo had access to historical operation data. This allowed data collection to be performed in parallel with the BIM–to–3D modeling. These data files include:

1. Energy consumption patterns
2. Occupancy data
3. HVAC operational metrics
4. Environmental conditions
5. Occupancy schedules

With these data files collected, model calibration could commence.

2.2.2 Model Calibration

Once the 3D model was made, the 12-month historical data was used to calibrate the virtual Digital Twin to determine areas of modification to match reality. According to the HY process, the calibration compares the simulated metered electricity consumption with the actual metered results. This calibration includes solar insulation and wind pattern simulations as they affect energy consumption relating to lighting use and cooling requirements. Validation is performed against ASHRAE guidelines.

To enhance the credibility of this process, HY supports using the methodology recommended by the Chartered Institution of Building Services Engineers Technical Manual 63 (CIBSE TM 63). HY's nine-step process closely follows the recommended approach outlined in TM 63. Specifically, TM 63 highlights the importance of collecting accurate data on building operations, including HVAC schedules, plug loads, occupancy patterns, and other relevant factors. This comprehensive data collection process, as recommended by CIBSE TM 63, is integrated into HY's model calibration efforts to effectively reduce the 'Performance Gap' between the model and reality.

To evaluate the calibration of the model, both the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE) are used.

The NMBE measures the bias in a model's predictions relative to the observed values, offering insights into the overall tendency of the model's errors and potential biases in its predictions.

The CVRMSE offers a normalized measure of the model's predictive accuracy, facilitating comparisons across different models or datasets. Specifically, the CVRMSE assesses the magnitude of the model's errors relative to the mean of the observed values, with lower CVRMSE values indicating better model performance.

The NMBE and CVRMSE are calculated as follows using the equations below:

$$CVRMSE = 100 \times \frac{\left[\frac{(\sum(y_i - \hat{y}_i)^2)}{(n-p)^{\frac{1}{2}}}\right]}{\bar{y}}$$

$$NMBE = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{(n-p) \times \bar{y}}$$

In these equations, the above parameters are as follows:

y_i: The observed value at the *i*th time step
$\hat{y}_i$: The predicted value at the *i*th time step
n: The total number of observations
p: The number of predictors in the model
$\bar{y}$: The mean of the observed values

The result of the calibration is shown below in Figure 5 and Table 2.

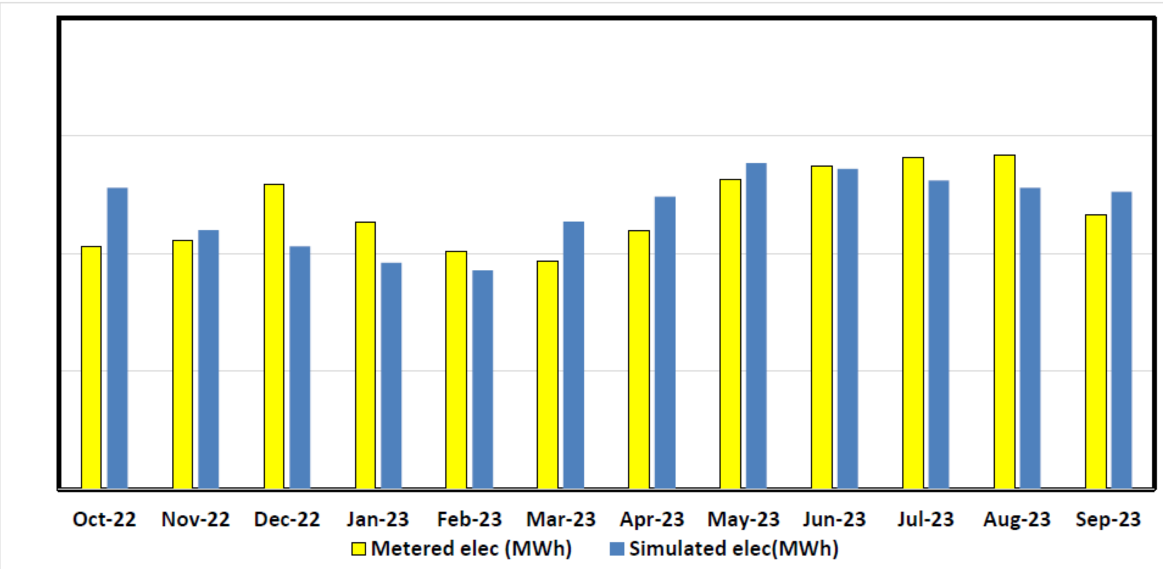

Figure 5 Belimo Model Calibration results in MWh

Electricity Consumption	Calibration Metric/Errors	Achieved	Max permitted ASHRAE Guideline 14
Total	NMBE - Overall Monthly	0.01	± 5%
	CVRMSE- Overall Monthly	12.94	15%

Table 2 Calibration results using NMBE and CVRMSE. Results show that the calibration of the model is within ASHRAE standards

Based on the calibration, the achieved NMBE value of 0.01% indicates minimal bias in the model's predictions, well within the ASHRAE Guideline 14 limit of ± 5%. The CVRMSE value of 12.94% demonstrates satisfactory predictive accuracy, also within the ASHRAE Guideline 14 limit of 15%. All indications point to a high level of accuracy with the developed model.

In Figure 5, we can see that the simulated results show larger variations in October 2022 and December 2022 to January 2023. This larger variation could be due to environmental factors not included in the data sets. However, with the calibration achieving an overall approximate 90% accuracy, the variations in accuracy for the 3-month highlight are considered insignificant in the overall results.

This high overall model accuracy stems from Belimo's access to high-quality historical operational data emphasizing the importance of data in building a successful Digital Twin model.

The calibrated model was further simulated over a 365-day period using weather data from 2023's Climate Forecast System Reanalysis (CFSR) to predict the baseline energy end-user breakdown. The simulation results show that the total cooling or total HVAC systems account for at least 28.7% of the end-use breakdown. These results are shown below in Figure 6. With simulation and calibration completed, the ECM study can be performed.

In Figure 6, the Digital twin model shows a simulated breakdown of energy usage for Belimo CESIM. This breakdown shows he 'process' accounts for the majority of energy consumption. 'Process' includes computers, monitors, and machinery operated by Belimo CESIM.

This breakdown also highlights the need for Belimo CESIM to implement further sub-metering in various sections, including Process, and Interior Lighting, to identify areas for more precise conservation.

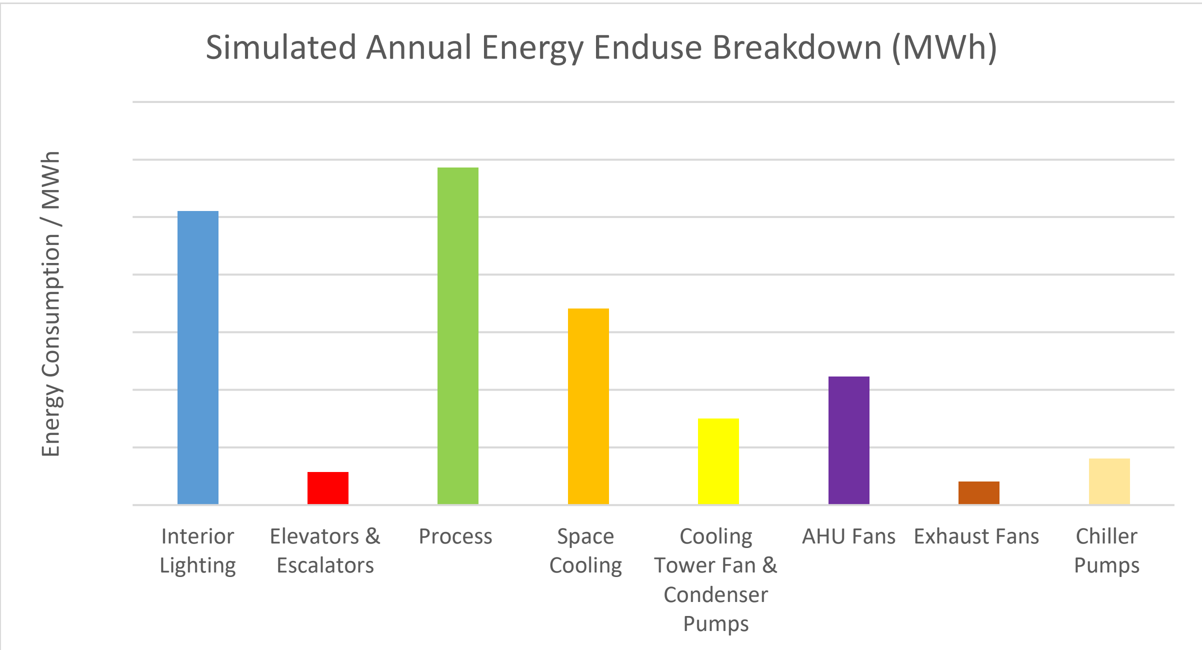

Figure 6 Calibrated Model end-use simulation breakdown

2.3 Third Phase: Deliverables and Strategy

2.3.1 ECM Strategizing

For Belimo, different Environmental Conservation Measures (ECMs) were simulated to assess their impact. The ECMs included:

1. **No-CAPEX measures**: Raising cooling setpoints, optimizing AHU operation schedules
2. **Minimal-investment measures**: Electrical outlet timers, feedback control
3. **Large-investment measures**: Building-integrated photovoltaic (BIPV) panels, retrofitting HVAC components

Simulations identified potential savings and payback periods, ranking ECMs based on investment requirements, energy savings, and return on investment. The results of the ECM study and subsequent recommendations are summarized below in Tables 3 and 4.

S/N	Energy Conservation Measure	Recommended (Yes/No)	Energy savings (%)	Payback (Years)
ECM2	Elevated Cooling Setpoint	Yes	1.2	-
ECM3	AHU Operation Shift	Yes	3.9	-
ECM4	Raise AHU Airside Supply Air Temperature	No	(0.7)	-
ECM5	Chilled Water Supply temperature raised	Yes	3.7	-
ECM6	Chilled Water Supply temperature reset	Yes	7.1	-
Cumulative			**15.9**	**-**
ECM1	Install Electrical Outlet Timers	Yes	2.3	2
ECM7	Larger Chiller and Smaller Pump Operation	Yes	4.7	0.25
ECM8	Natural Draft Cooling Tower	No	(1.1)	
ECM10	Demand Control Ventilation Floor	No	4.6	-
Cumulative			**22.9**	**2**
ECM11	Building Integrated PV	Yes	15.6	10
Cumulative			**38.5**	**10**
ECM9	*Low Emissions External Glazing Film*	*No*	*1.1*	*50*

Table 3 Recommended ECMs with energy savings and payback

S/N	Energy Conservation Measure	Energy savings (%)	Payback (Years)	Cost (US$'000)
ECM1	Install Electrical Outlet Timers	2.3	2	0.5
ECM7	Larger Chiller and Smaller Pump Operation	4.7	0.25	0.2
ECM11	Building Integrated PV	15.6	10	431

Table 4 Cost for Implementation of ECMs

Summarized in Table 4 is the cost for the recommended ECMs. In total, implementing all of these ECMs to achieve maximum energy savings would cost approximately US$433,000 with an overall payback period of 10 years.

2.3.1.1 ECM Description

ECM 1: Installing Electrical Outlet Timers

Electrical outlet timers play an essential role by effectively controlling electrical outlets. By automatically turning off non-essential devices during periods of inactivity, these timers greatly reduce operational energy consumption. This allows non-critical devices, such as printers, monitors, and various appliances, can be unplugged during off-peak hours, resulting in substantial energy savings and a smaller carbon footprint. Embracing electrical outlet timers is an intelligent investment for a more sustainable future.

An example of this is a 10kW load operating for 8 hours instead of 10 hours saving 2 hours of energy or 10kWh.

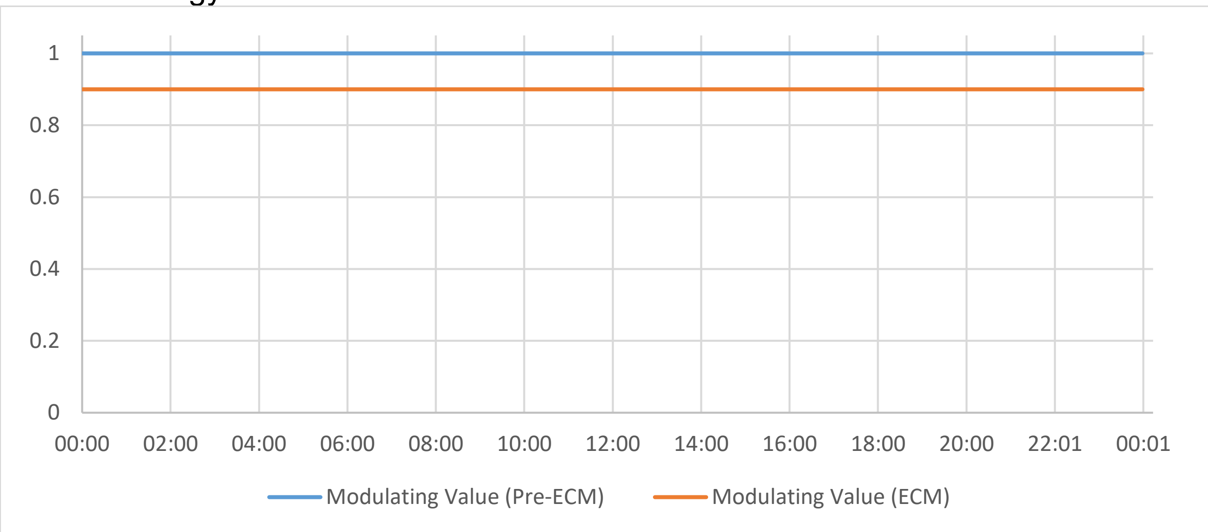

Figure 7 Operating load of the Electrical Outlets before ECM installation. Operating load of the outlets dropping to 90% after installation of the ECM.

Based on the simulation, using Electrical Outlet Timers will reduce the operating load to 90% of the original operating time resulting in 2.3% energy savings.

ECM 2: Elevated Cooling Setpoint

Elevating the cooling setpoint from 24°C to 25°C reduces energy consumption by lowering the cooling load. A higher setpoint decreases the temperature (ΔT) difference between indoor and outdoor environments, reducing the required cooling capacity. This adjustment results in decreased compressor runtime, leading to significant energy savings. The reduction in cooling demand directly impacts compressor energy use, calculated as:

$$Q_c = mC_p\Delta T$$

Where:

- Q_c: Cooling load
- m: Air mass flow rate
- C_p: Specific heat
- ΔT: Temperature difference between supply and return air

For example, reducing the cooling load by 10% can lead to substantial energy savings in tropical climates like Mumbai, where cooling is a significant energy expense.

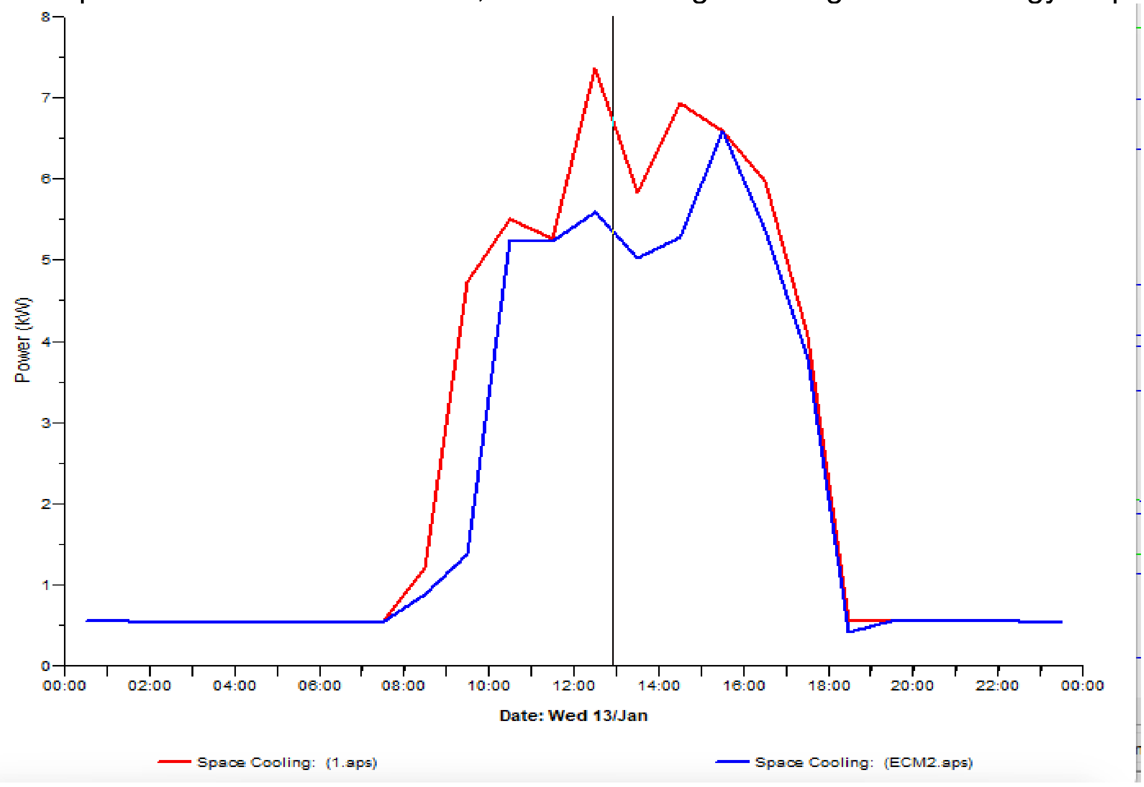

Figure 8 Elevated cooling setpoint results in lower power requirement (in blue) compared to pre-ECM

Based on the simulations, by integrating the area under the curves the blue line (ECM line) shows a lower energy consumption resulting in 1.2% energy savings.

ECM 3: AHU Operation Shift

Adjusting the Air Handling Unit (AHU) operating hours to better align with occupancy patterns can significantly reduce energy consumption. For instance, starting the AHU earlier and shutting it down earlier ensures that cooling and ventilation are only provided when necessary. This strategy minimizes wasted energy during unoccupied periods. Energy savings primarily come from reduced fan power consumption, calculated as:

$$Savings\ (kWh) = Fan\ Power\ (kW) \times Reduced\ Hours\ (h)$$

An example of the savings is a 10kW shutting off two hours earlier can save approximately:

$$Savings\ (kWh) = 10\ (kW) \times\ 2\ (h) \times 365\ (d) = 7{,}300kWh$$

This measure reduces both operational cost and carbon footprint.

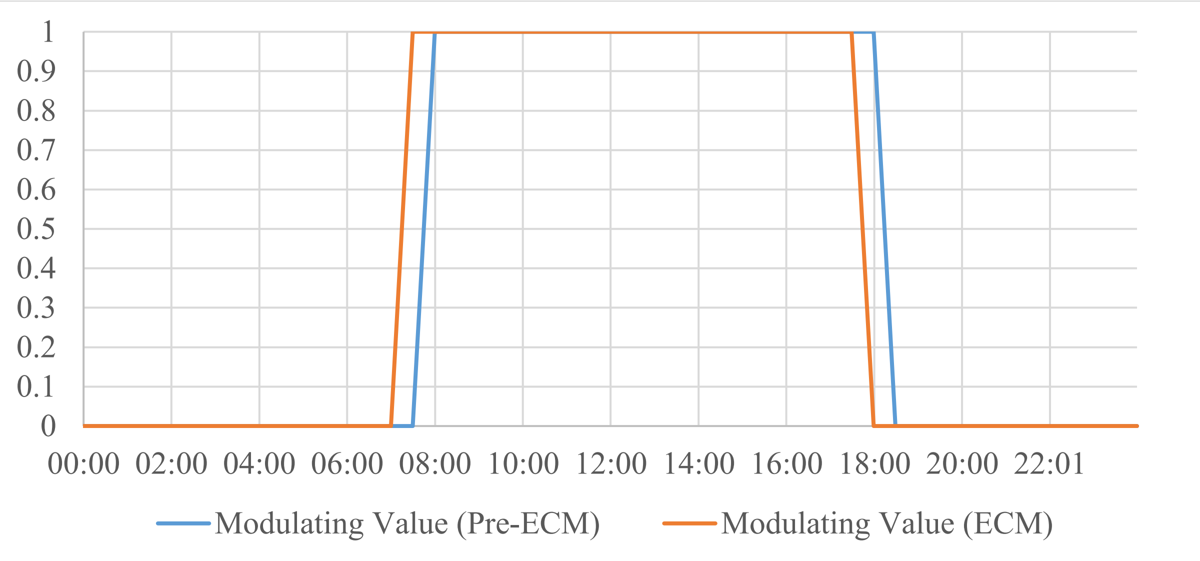

Figure 9 Operating Load of the AHU before ECM shift. AHU operating load shifted to start earlier and shut down earlier to save energy

As observed in Figure 9, by shifting the AHU operation earlier by just 30 minutes, the AHUs would only operate when Belimo CESIM is occupied. By starting 30 minutes in advanced, the AHUs will be able to cool the facility before the cooling load increases and reduces the initial effort by the AHUs to cool an already loaded environment. This results in the savings of about 6.3%.

ECM 4: AHU Supply Temperature Reset

Raising the AHU supply air temperature (SAT) from 18°C to 20°C decreases the cooling energy required to condition the air. A higher SAT reduces the latent cooling load (moisture removal), which is a key factor in energy consumption in HVAC systems. The decrease in latent and sensible cooling energy is quantified as:

$$Q = mC_p\Delta T$$

Where:

- Q: Cooling energy
- m: Air mass flow rate
- C_p: Specific heat
- ΔT: Temperature difference between supply and return air

In the context of Belimo, this ECM, when combined with the others, resulted in a 0.7% increase in energy consumption, making it unsuitable for implementation.

ECM 5: Chiller Water Supply Temperature Raised

Raising the chilled water supply temperature from 8°C to 10°C improves chiller efficiency by reducing the temperature lift—the pressure difference between the evaporator and condenser. This reduces the energy required for compression. Chiller compressor power is governed by:

$$P_{comp} = \frac{Q_c}{COP}$$

Where:

- P_{comp}: Compressor Power
- Q_c: Cooling Load using the equation $Q = mC_p\Delta T$
- COP: Coefficient of performance. Assume

In Belimo CESIM's context, increasing the temperature by 2°C reduces the cooling load and subsequently decreases the compressor power, resulting in approximately 3.2% energy savings while maintaining indoor comfort levels.

ECM 6: Chilled Water Supply Temperature Reset

This measure dynamically adjusts the chilled water temperature based on cooling demand. During periods of low demand, the chilled water temperature is increased, reducing compressor power consumption. The adaptive resetting improves the chiller's coefficient of performance (COP), dynamically lowering energy use. For example, this strategy minimizes compressor runtime and reduces overall energy use while maintaining efficient cooling.

ECM 7: Larger Chiller and Smaller Pump Operation

Operating a larger, more efficient chiller with smaller pumps can optimize system energy use. Smaller pumps operating at lower frequencies consume less power due to the affinity laws, which state:

$$P_{pump} \propto Q^3$$

Where:

- P_{pump}: Pump Power
- Q: Flow rate

Using a larger more efficient chiller, will reduce the required chilled water quantity. This leads to lower flow rates through smaller pumps, which can decrease energy consumption and operational costs.

ECM 8: Natural Draft Cooling Tower

A natural draft cooling tower is a type of cooling tower that can be switched off at times of low heat load (e.g., such as at night). Natural draft cooling towers have designs that allow the use of natural convection of the air without needing fans.

Reducing fan use at night would result in lower energy consumption by the cooling tower and decrease operational costs related to energy and maintenance.

However, due to the high latent loads caused by high humidity in Mumbai, using natural draft cooling towers is not feasible and based on simulations, is likely to increase energy consumption by 1.1%.

ECM 9: Low Emissions External Glazing Film

Low emissions external glazing film is a type of film attached to building windows to reduce the heat entry.
This ECM is a passive system that would lower the building's cooling requirement during the day when the heat entry is at its highest.

ECM 10: Demand Control Ventilation Floor

Using CO_2 and VOC sensors to modulate ventilation based on occupancy and indoor air quality (IAQ) reduces unnecessary airflow during low-demand periods. Ventilation energy is proportional to airflow:

$$Ventilation\ Energy \propto Airflow$$

Reducing airflow, lowers both fan and cooling energy consumption. In Belimo CESIM, this ECM could reduce energy consumption by 4.6% as the demand control ventilation would reduce both AHU and cooling energy when occupancy is low.

However, based on conditions experienced in the Belimo CESIM building and the presence of other variable speed equipment, it was determined that ECM 10 would be redundant and would not be implemented.

ECM 11: Building-Integrated Solar PV

Installing photovoltaic (PV) panels on building facades generates renewable electricity and provides additional insulation. This measure reduces dependency on grid power while lowering cooling loads. Solar energy generation is calculated as:

$$Solar\ Energy\ (kWh) = Panel\ Area\ (m^2) \times Efficiency\ \times Solar\ Irradiance\ (\frac{W}{m^2})$$

where:

- Panel area: Total area of installed PV panels
- Efficiency: Panel efficiency
- Solar Irradiance: Incident solar radiation

ECM 11 is currently in the process of being designed and studied for feasible implementation.
Based on the simulations performed, the ECM's cumulative effect is shown in the Waterfall chart in Fig 10, which is based on the 7 ECMs from Table 3 above.

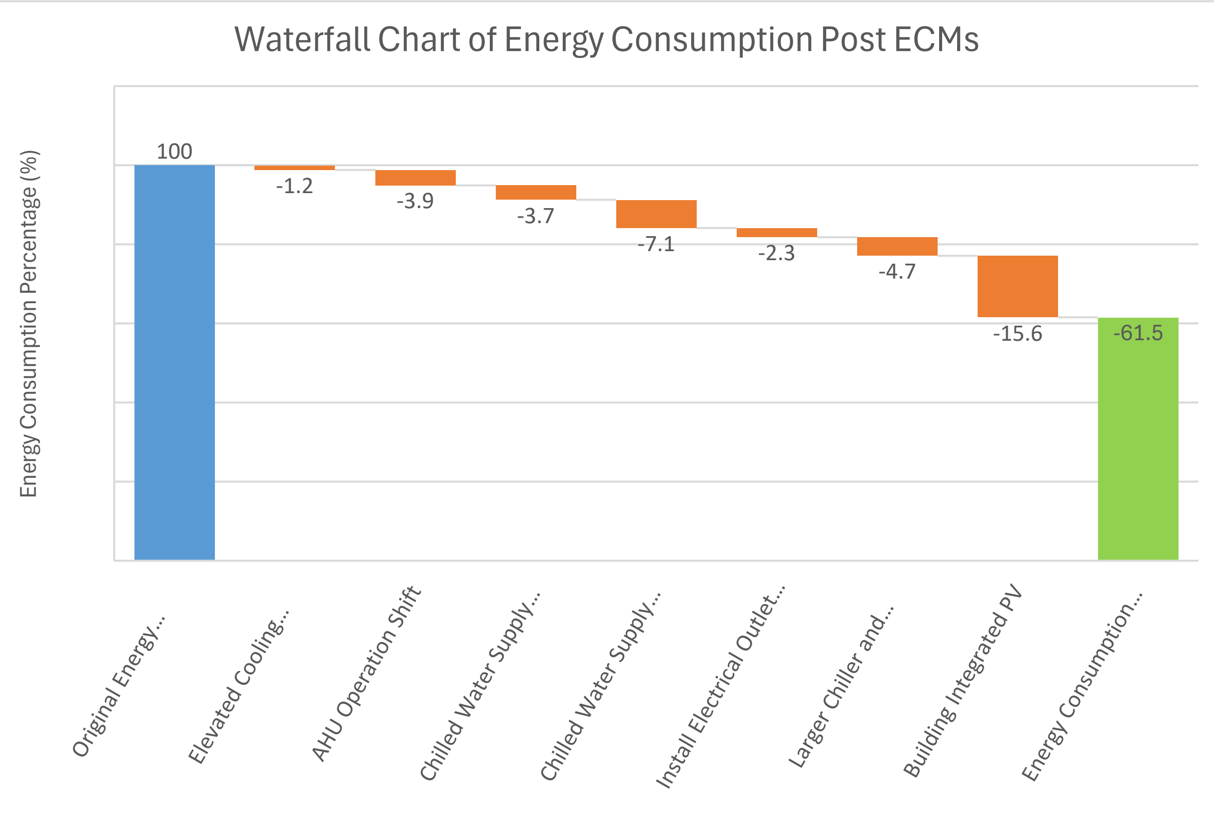

Figure 10 Waterfall chart indicating ECM savings

Based on the ECM simulation study, several measures were found to yield immediate high energy savings including:

1. AHU operation shift reduced energy use by 6.3% with no extra cost
2. Elevated cooling setpoint reduces energy use by 6.3% with no extra cost

These ECMs could be implemented immediately without CAPEX investments providing immediate savings and bottom-line value to the client.

Overall, the ECM study recommended the following scenarios with their estimated costs which were obtained from simulating the necessary investment required:

1. **39%** energy savings with an investment of **$551,000** and a **payback period of 10 years**.
    a. Included in this option are ECMs that bring the company toward Net-Zero;

2. **22.9%** energy savings with an investment of **$800** and a **payback of 2 years**.
    a. No options to bring the company towards Net-Zero included

3. 15.9**%** immediate energy savings with **no initial investment**.
    a. No options to bring the company towards Net-Zero included

Once the ECMs were proposed, the Belimo team immediately started identifying which ones could be implemented. After an initial study, the following ECMs were chosen for immediate implementation.

Their status as of January 2025 is also summarized below.

	ECM Item	Status
ECM 1	Install Electrical Outlet Timer	Implemented
ECM 2	Elevated Cooling Setpoint	Implemented
ECM 3	AHU Operation Shift	Implemented
ECM 5	Chilled Water Supply Temperature Raised	Attempted to implement but faced challenges during testing and did not proceed
ECM 6	Chiller Water Supply Temperature Reset	Not implemented due to challenges faced with ECM5
ECM 7	Large Chiller and Smaller Pump Operation	Partial implementation of smaller pump operation aligned with Belimo's earlier strategy.
ECM 11	Building Integrated Photovoltaics	In-progress

Table 5 Status of ECM implementation as of January 2025

In summary, Belimo has already implemented *3.5* ECMs as of January 2025. This low number of implementations is due to of challenges in equipment settings such as at the chiller plant. As a result ECMs 5 and 6 were not implemented. This means that a total of 3.5 out of 5 ECMs have been implemented by January 2025, with one more ECM in the process of being implemented.

This deliverable is key for Belimo to make informed strategic investments towards Net-Zero. Since any investments requiring millions of dollars require due diligence, this ECM study provides Belimo management with further in-depth, scientifically supported analysis for decision-making.

2.3.2 Digital Twin Creation

The next deliverable was the calibrated Digital Twin, which was delivered, and integrated with real-time data streams. The Digital Twin was programmed to support predictive maintenance and monitor asset performance, enabling proactive decision-making.

A screenshot of the Digital Twin delivered is seen below in Figures 11 – 13.

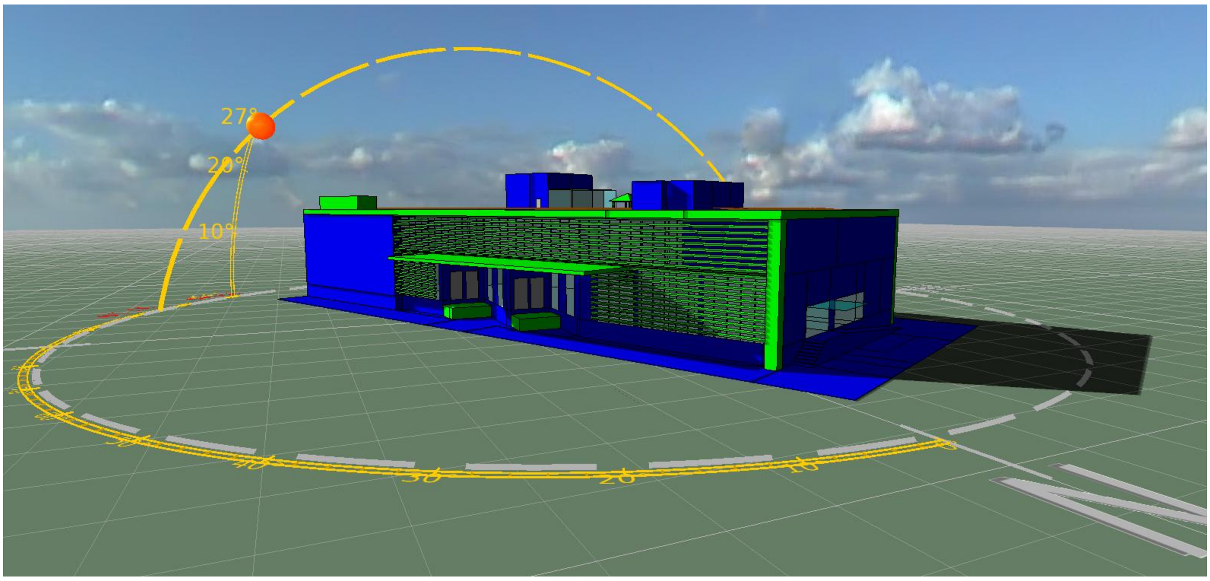

Figure 11 IESVS 3D model of CESIM

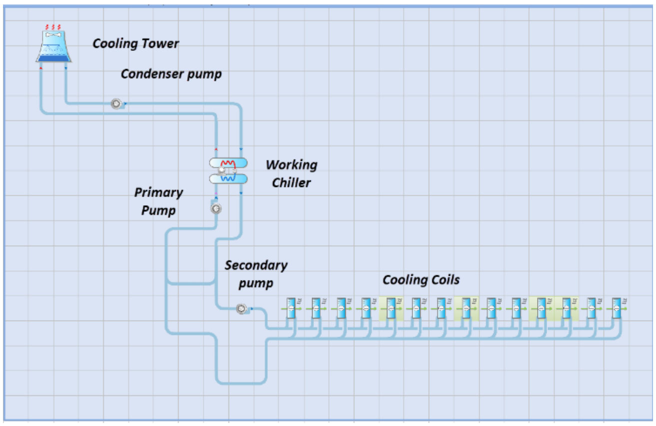

Figure 12 HVAC Water Side Digital Twin layout for CESIM

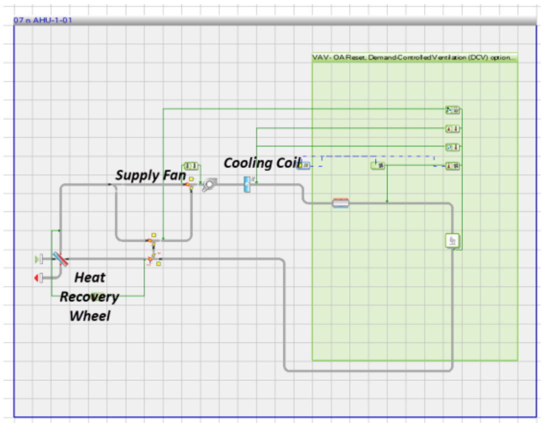

Figure 13 HVAC Air Side Digital Twin layout for CESIM

The Digital Twins were developed using IESVE – Integrated Environmental Solutions Virtual Environment. The Digital Twins, as shown in Figures 11 – 13 above, consist of two parts: the 3D model and the HVAC layout. Both drawings are combined to create the Digital Twin used by HY to perform the ECMs and subsequently by Belimo to continue monitoring operations.

2.3.3 Interactive Dashboard

The final deliverable is a user-friendly dashboard designed to provide real-time visualizations of key performance indicators (KPIs) such as energy efficiency, carbon footprint, and operational status. The dashboard enables management to interact with the Digital Twin, improving their ability to track sustainability goals and operational efficiency.

A screenshot of the dashboard is shown below in Figure 14. The dashboard is programmed to refresh every 5 seconds.

Figure 14 Azendian Interactive ESG Dashboard. Dashboard refreshes every 5 seconds

3. Value Proposition

When the project started, the Digital Twin was implemented to reduce Belimo's energy consumption, and in turn, lower their operational energy expenses. As mentioned in the previous section, a total of 3.5 ECMs were implemented. To assess the value of the project, we compared the energy costs Belimo paid after the ECMs were implemented.

The following assumptions were made regarding the expected energy savings:

1) Power load demand remained constant from 2023 – 2024
2) Electricity rates remain relatively constant
3) Electricity fixed costs remain constant

Comparing the costs spent by Belimo between 2023 and 2024, the percentage difference is seen below in Table 6:

Month	Percentage increase
Jan	8%
Feb	5%
Mar	14%
Apr	18%
May	22%
Jun	-100%
Jul	23%
Aug	18%
Sep	12%
Oct	9%
Nov	3%
Dec	16%

Table 6 Comparison of Energy bills between 2023 and 2024

On an initial observation, the increase in energy costs was counter-intuitive to the expected outcome. A deeper dive into the numbers provided by the energy bills revealed several factors which consist of the following:

1. There was an increase in power demand load by 8% between 2023 and 2024
2. Electricity rates had increased between 3% - 18% depending on the month
3. There were changes in various fixed rate charges due to external factors

Hence, it was inaccurate to conclude that the various ECMs negatively affected the cost. These observations also invalidate the original assumptions HY made about how to determine energy savings.

To accommodate the dynamic nature of the industry, a new objective approach was required to analyze and determine if the ECMs provide some energy savings after considering the changes of the energy use and costs. This approach is described in the next sub-section.

3.1 Dynamic Energy Component Adjustment Forecasting (DECAF)

Dynamic Energy Component Adjustment Forecasting (DECAF) is a method proposed by HY to analyze the savings achieved by implementing the ECMs in a dynamic environment and to forecast the expected savings if the ECMs had not been implemented.

In the case of Belimo, the goal is to estimate what the monthly payments in 2024 should have been, given:

1. The observed percentage changes in billing components (e.g., energy rate, interest charges, etc.) between 2023 and 2024.
2. The increase in contracted kVA loads from 2023 to 2024.
3. The contribution (weight) of each component to the total payment in 2023.

This allows for a direct comparison between **expected payments** and **actual payments**, offering insights into cost efficiencies or discrepancies.

3.1.1 Methodology

3.1.1.1 Data Inputs

The analysis was based on monthly billing data for 2023 and 2024, including:

- Monthly total payments for each year.
- kVA load per month
- Percentage changes in each billing component between 2023 and 2024.
- Weights of billing components in 2023.

3.1.1.2 Calculation Framework

Adjusted Component (2024): For each billing component for each month, the adjusted cost for 2024 was calculated as:

$$Adjusted\ Component\ (2024) = Total\ Paid\ (2023) \times Weight\ (2023) \times \left(1 + \frac{\%\ Difference}{100}\right) \times \frac{kVA\ Load\ (2024)}{kVA\ Load\ (2023)}$$

Key Variables:

1. **Total Paid (2023):** The total monthly payment for all components in 2023 for a given month.
    - Serves as the baseline for proportional adjustments.
    -
2. **Weight (2023):** The proportion of a specific billing component's cost in the total payment for that given month in 2023.
    - Formula:
    $$Weight\ (2023) = \frac{Component\ Cost\ (2023)}{Total\ Paid\ (2023)}$$
    - Ensures that components are scaled proportionally to their contribution in 2023.
    -
3. **% Difference:** The observed percentage change in the component's cost between the given month 2023 and subsequently in 2024.
    - Captures how each component's cost has increased or decreased.
    -
4. **kVA Load (2023) and kVA Load (2024):** The contracted kVA load for the given month.
    - Scales the component costs to reflect higher or lower energy usage.
    -

Logic of the Equation:
The equation combines several adjustments:

1. **Baseline Scaling:** Starts with the total payment in the given month in 2023 and scales it by the component's contribution (weight).
2. **Inflation Adjustment:** Applies the percentage increase to reflect changes in component pricing from 2023 to 2024.
3. **Load Adjustment:** Scales the adjusted component further based on changes in kVA load, ensuring that increased energy demand in 2024 is reflected in the expected payment.

This method ensures that each component's cost for 2024 is proportionally adjusted to account for both price changes and increased energy usage.
Expected Total Paid (2024): The expected total payment for 2024 was calculated by summing the adjusted costs for all components:

$$Expected\ Total\ Paid\ (2024) = \sum_{Components} Adjusted\ Component\ (2024)$$

Difference and Percentage Difference: The difference between expected and actual payments was calculated as:

$$Difference\ (INR) = Expected\ Total\ Paid\ (2024) - Adjusted\ Total\ Paid\ (2024)$$

The percentage difference was:

$$\%\ Difference = \frac{Difference\ (INR)}{Actual\ Paid\ 2024} \times 100$$

3.2 Updated Findings using DECAF

Using the DECAF methodology, the percentage difference between the expected charge and the actual charge from July 2024 – December 2024 is summarized below:

Month	Percentage Difference between expected and actual payment
Jul	8.5%
Aug	9.6%
Sep	19.9%
Oct	21.2%
Nov	11.3%
Dec	10.1%

Table 7 Percentage Savings for Belimo CESIM after use of DECAF

The results shown were only from July to December as all the ECMs used were completed by June 2024. The results from the DECAF framework indicated savings between 8.5% - 21.2% depending on the month. This result indicates that Belimo would have had to pay about 15% more on energy bills on average without the ECMs.

Based on the findings, the ECMs recommended indeed provided value to Belimo through operational savings after accounting for the increase in power load and rise in energy prices.

3.3 Net-Zero Investment Strategies

The next value proposition Belimo obtained was a net-zero investment strategy approach. Through the Digital Twin, the model suggested using Low-Emissions External Glazing Film and additional BIPV.

The model was able to determine that the Low-Emissions External Glazing Film would have ab10-year ROI, making this option not feasible. However, adding more BIPV results in a 2-year ROI, making it a better investment. Additionally, using BIPV panels would bring Belimo CESIM closer to net-zero and reduce current energy consumption by 9% based on 2023 consumption data.

Overall, the Belimo project successfully applied and validated HY's proposed 3-Phase Digital Twin development framework to meet Belimo's sustainability goals. These value propositions position Belimo as a leader and an example of the standards the built environment must reach by using the Digital Twin to improve overall sustainability.

4. Additional Value-Added Services Provided

In addition to the immediate energy savings provided by the Digital Twin, this proof of concept expanded to include transforming the Digital Twin from a static analysis model to a dynamic one using it to determine building modification investment strategies. This section will cover these expanded proof of concepts that Belimo used to maximize the Digital Twin's value for both daily operations and long-term strategic investments.

4.1 Dynamic Digital Twin Transition

In response to the cost savings achieved through the ECM measures recommended, Belimo requested that HY extend the use of the Digital Twin to optimize daily operations. To facilitate this transition, the static Digital Twin was uploaded to a platform called iScan, an IES platform that connects data from sensors, meters, and systems linked to the BMS to the Digital Twin. This enables predictive analytics and the provides recommended actions for the Facilities Management (FM) team to implement.

4.1.1 Real-time Energy Savings

Data observed by iScan indicated that Belimo currently operates two chillers at reduced loads, resulting in energy wastage as seen in Fig. 15 below:

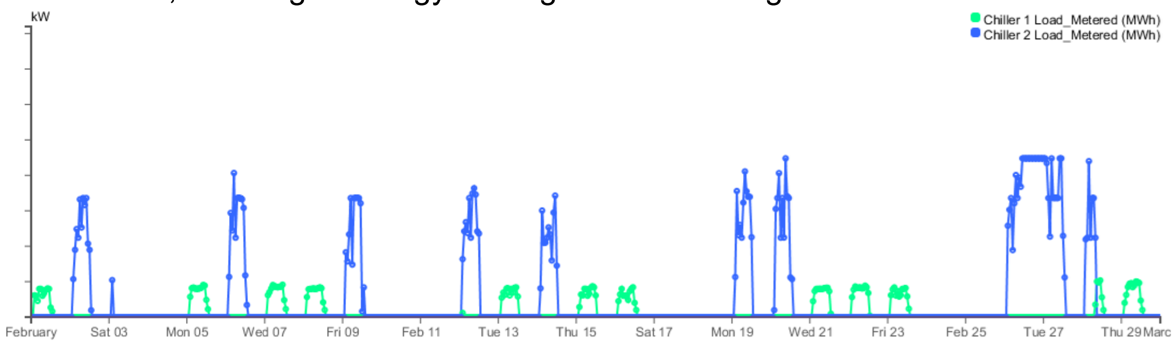

Figure 15 shows data indicating Chiller 1 operating in low and inefficient modes and at times not needed as seen from the dates starting on Wednesday 21 onwards

The second chiller also operates at a lower load, leading to a lower coefficient of performance (COP) and inefficient operation due to the reduced loads. The chiller operations appear to be irregular, with instances where both chillers run simultaneously and one operates at a significantly low load, which further wastes energy. iScan recommended operating a single chiller at its optimal load range until the load exceeds the chiller's maximum capacity. This approach will optimize energy efficiency and lead to energy savings.

In another instance, iScan observed through historical operating data that the chiller energy consumption pattern, when comparing simulated and metered energy, reveals variations in the internal loads of building operations during specific months as seen in Fig. 16 below.

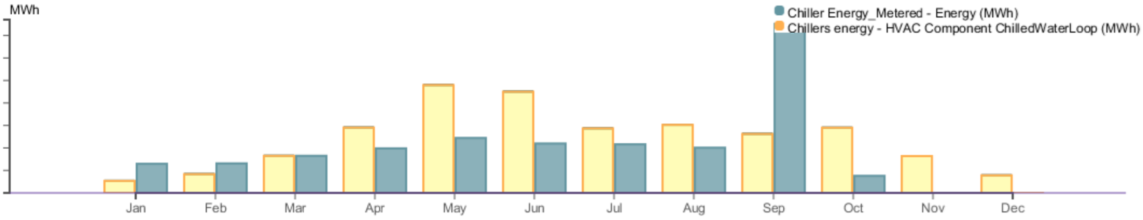

Figure 16 iScan Analytics observing a large variation between recorded data and simulated energy consumption for month of September

Conducting future predictive analysis will support better decision-making and provide insights into the loading patterns for chillers. This will help identify periods of higher consumption and facilitate more effective planning for future operations. Furthermore, observing higher chiller consumption at lower loading levels indicates suboptimal sequencing. It is recommended to perform predictive analysis for the next two years using future weather files to understand these patterns and forecast consumption accurately. This approach offers added value through potential energy savings and an enhanced user experience.

4.1.2 Sub-Metering identification

The comprehensive summary of the simulated data, including both total and individual end-uses, helps identify high-consumption end-uses for energy optimization purposes as shown in Fig. 17.

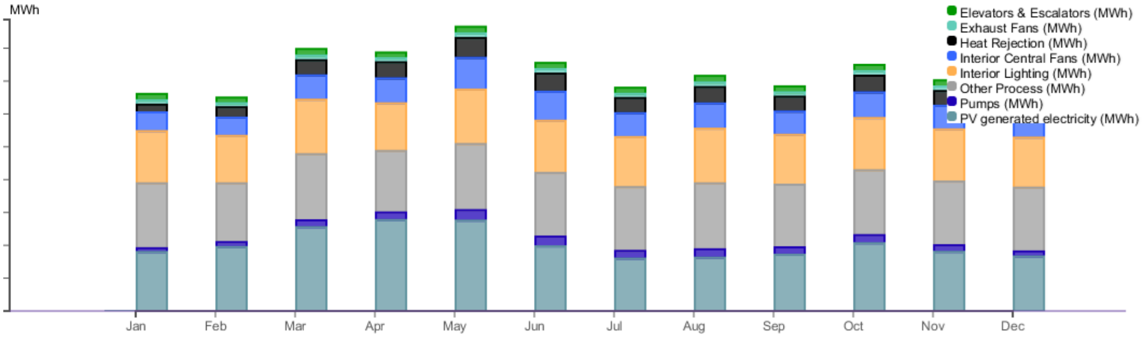

Figure 17 Energy Consumption of Belimo CESIM Over 12 months by application

However, due to the absence of sub-meters connected to the Building Management System (BMS), a comparative analysis is currently not feasible. Sub-metering can be strategically planned during future expansions. The installation of sub-meters is strongly recommended to enhance energy identification, facilitate further optimization, and ultimately contribute to energy savings.

4.1.3 Identifying System Inefficiencies

An example of inefficiency identified is the airflow volume of Belimo's AHUs. The monthly total of airflows between Air Handling Units (AHUs) can help identify operational anomalies within AHU systems. Solar load variations across different months should be reflected in the supply flow, with warmer environments requiring increased cooling, as supported by simulated data. However, data from March to September indicates a constant airflow, suggesting inefficient system operation during these months as shown in Fig. 18 below.

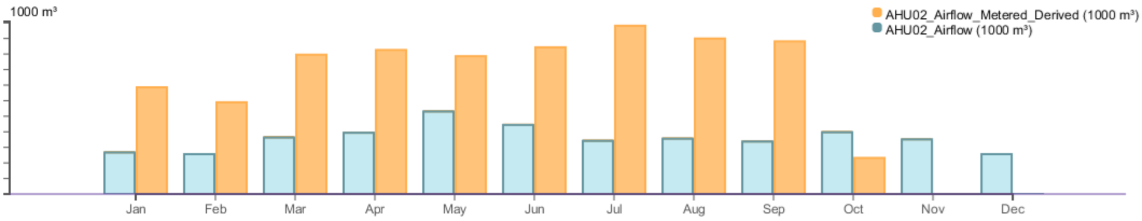

Figure 18 Comparison of simulated AHU airflow with recorded BMS data

To optimize performance, it is recommended to measure both airflow and CO2 levels. This data can assist in adjusting fresh air intake and supply flow according to space demands, ensuring optimal system efficiency. Implementing these adjustments not only enhances energy savings but also improves the overall user experience.

These are some examples of the additional value that converting the Digital Twin from a static model to a dynamic model provides: optimizing the day-to-day system operation for further savings beyond the one-time ECM measures.
Beyond operational savings, the Digital Twin model also aided Belimo in long-term strategic planning by enabling cost-effective capital expenditures (CAPEX) savings on modifications for the Belimo CESIM building.

4.2 Digital Twin Long-term Building Modification Strategy Simulation

For any company, having a long-term business strategy is crucial. Belimo, like other organizations, aims to enhance its manufacturing output while simultaneously adhering to its Sustainable Development Goals (SDGs). To achieve its long-term growth objectives, Belimo has resolved to expand the floor area of Belimo CESIM by adding two additional floors.

Initially, Belimo's management expressed concerns regarding the potential need for additional chillers due to the expansion. To ascertain the appropriate size of the chiller, Belimo sought the assistance of HY to employ the Digital Twin technology. This approach facilitated the simulation and determination of the necessary chiller capacity.

Utilizing the Digital Twin, Belimo concluded that, based on the anticipated design modifications for Belimo CESIM, the projected increase in energy consumption would be as follows:

Baseline Energy Consumption for Current Configuration (MWh)	Baseline Energy Consumption for Future Configuration (MWh)
277.2	576.5

Table 8 Energy Consumption of Chillers between old CESIM configuration and new configuration

Based on the simulation, adding more floors would require a 108% increase in energy consumption. However, the simulation showed that the current HVAC Chiller capacity could handle the increased energy needs. Consequently, this led to substantial CAPEX savings for Belimo, improving their cash flow outlook. The results from the Digital Twin simulation provided valuable assurance to management, supporting both sustainability efforts and future CAPEX planning.

Furthermore, with the CAPEX savings from this study, Belimo aimed to see if these savings could be redirected towards increasing their on-site green energy production to transition Belimo CESIM to Net-Zero. To achieve this, Belimo hired HY to simulate various configurations and evaluate their potential for energy generation.

HY collaborated with Belimo and refined the configurations to the following:

1) Additional solar panels on the remaining clear rooftop area
2) Additional solar panels installed over the pavement cover
3) Additional solar panels installed over the south side driveway

The Digital Twin simulation revealed the following additional energy generation was determined after an entire year of operation:

Configuration Number	Energy Generated (MWh/yr)
1	23.2
2	48.09
3	37.7

Table 9 Energy generation per annum for each solar panel configuration

This supplementary exercise evaluated Belimo management on the increased solar potential of the Belimo CESIM building, fostering an informed discussion that helped guide Belimo CESIM toward reaching net-zero emissions while also considering long-term capacity expansion.

5. Lessons Learned

This project represented Belimo's first attempt at implementing a Digital Twin with a dashboard as part of its broader decarbonization and sustainability initiatives. As a **First-Of-A-Kind (FOAK)** project, it introduced new challenges and opportunities for learning, particularly in the areas of **system integration, data management, and project planning**. The insights gained from this experience have provided valuable takeaways that will inform future implementations and optimize the effectiveness of digital transformation efforts in building management.

5.1 Streamlining and Centralizing BMS

A key lesson from the project was the **critical importance of streamlining and centralizing building monitoring systems.** Many buildings currently rely on multiple, siloed platforms to manage HVAC, lighting, energy consumption, and other infrastructure components. This fragmented approach leads to operational inefficiencies, limits data integration, and obstructs the ability to obtain a holistic view of system performance. The project highlighted the value of consolidating these functions into a single, centralized Building Management System (BMS). A unified BMS simplifies operations, resolves interoperability issues, and ensures that essential building data is captured in one platform—improving the accuracy and reliability of insights used to support decarbonization efforts. However, the integration process for this project also revealed limitations in data transparency, particularly in terms of metering granularity and subsystem compatibility. These findings underscored the need for a formal BMS audit to systematically assess current capabilities and identify areas for enhancement before embarking on a Digital Twin project.

5.2 Availability of Metering

Another critical finding was that **the effectiveness of the BMS depends on its ability to connect with meters and sub-meters throughout the building**. The more comprehensive the data collection, the deeper the insights that can be generated. In cases where the BMS lacked sufficient connections to sub-meters, it became difficult to achieve granular energy monitoring, which is essential for identifying inefficiencies, tracking energy use by specific systems, and making informed decisions about energy optimization. **Ensuring that a BMS is designed with robust connectivity to all relevant metering points from the outset** is essential for maximizing the value of a Digital Twin solution.

5.3 Suitable Data Pipelines

Data integrity and integration emerged as another major factor in the success of the project. The **flow of data from the BMS to the Digital Twin Dashboard must be carefully structured to ensure compatibility, accuracy, and relevance**. Sending data from multiple, uncoordinated sources often results in inconsistencies, making it difficult to perform reliable analytics and generate actionable insights. **For data-driven decision-making to be effective, it is crucial that all data points are standardized, synchronized, and of sufficient granularity**. High-level aggregate data may provide a general overview, but without granular details, deeper diagnostic and predictive capabilities are lost. This highlights the necessity of **establishing clear data**

governance protocols at the beginning of the project to ensure that only high-quality, actionable data is fed into the dashboard.

5.4 Pre-Project Analysis

Finally, one of the most valuable lessons from this initiative was the importance of **conducting a thorough pre-project analysis before formalizing commitments and commencing execution**. Digital Twin projects, particularly those that involve multiple stakeholders, require **clear definition of project scope, guardrails, and expectations** to prevent misalignment and scope creep. A structured pre-project phase allows for the identification of potential **integration challenges, data availability gaps, and system compatibility issues**, ensuring that solutions are incorporated into the project plan before implementation begins. By dedicating time and resources to a robust feasibility assessment, stakeholders can proactively address risks and design a solution that is both scalable and effective.

By applying these lessons to future projects, organizations like Belimo can enhance their approach to Digital Twin implementation, ensuring greater efficiency, better data insights, and stronger alignment with sustainability goals. This project has provided a strong foundation for refining digital transformation strategies in building management and underscores the critical role of **system integration, data governance, and strategic project planning** in achieving successful decarbonization outcomes.

5.5 Dashboard Limitation

Another area of limitations was the challenges arising from the absence of a centralized BMS data management system, which resulted in the limitations of the dashboard. Although the dashboard provided basic KPI tracking, the lack of dynamic analytics due to the inadequacy of the data pipelines in their setup diminished the value proposition of the dashboard for Belimo CESIM. Consequently, Belimo CESIM and the consultant gained valuable insights from this experience, emphasizing the importance of having suitable data pipelines already established to facilitate the dynamic analytics to be displayed on the dashboard.

6. Conclusion and Recommendations

This white paper has demonstrated the transformative potential of Digital Twin technology in driving sustainability within the built environment. By leveraging real-time data and advanced analytics, Digital Twins offer unparalleled insights and optimization opportunities, leading to more sustainable practices. While the data from Azendian's dashboard and iScan provide a basic framework for monitoring sustainability metrics, their limitations during implementation suggest room for improvement. Future versions may prioritize deeper analytics and real-time responsiveness.

Digital Twins present a powerful tool for driving sustainability in the built environment. By integrating real-time data and advanced analytics, they offer unparalleled insights and optimization opportunities, leading to more sustainable practices. Given the demonstrated efficacy of HY-BeeCon's 3-phase process, it is recommended that this approach be adopted as an industry standard. This framework not only addresses the technical aspects of Digital Twins but also prioritizes sustainability, making it a comprehensive solution for the built environment. By embracing this innovative technology and approach, the built environment can move towards a more sustainable and resilient future.

Belimo India Automation Pte Ltd has shown remarkable motivation and commitment to sustainability, utilizing access to over 4000+ data points to enhance energy efficiency and reduce waste. However, the limitations of the available solutions must be acknowledged. Many systems currently operate in silos, requiring special access for management, such as the chiller management system. This fragmentation hinders the full potential of integrated energy savings.

Belimo and HY invite the industry to explore the true potential of the energy dashboard and innovative technologies in predictive analytics through collaborative efforts. By inspiring innovation and conducting hackathons, stakeholders can collectively push the boundaries of what is possible, driving the built environment towards a more sustainable and resilient future.

Appendix A: Data Source Checklist for Digital Twin Development

Fixed Parameters			
Item	Priority	Part	Item
1	High	Building envelope	Architectural and Site Plan Layouts
2	High	Building envelope	Architectural elevation drawings showing the composition of the different façade or wall systems
3	High	Building envelope	Detailed thermal properties of the façade and external wall systems showing the thickness, U-value of external wall, roof, glazing, slab on grade, basement walls, partitions and floors. Also include SC of the glazing/roof light
4	High	HVAC (Water side)	Chilled Water Schematic / DX Schematic
5	High	HVAC (Water side)	Plan layouts showing the mode of ventilation (AC, MV, NV) for various spaces
6	High	HVAC (Water side)	Schedule of Chilled Water / Air Cooled Equipment (indicating quantity, location and operation mode)
7	High	HVAC (Water side)	Chillers Technical Specification
8	Medium	HVAC (Water side)	Pumps Technical Specification
9	Medium	HVAC (Water side)	Cooling Tower Technical Specification
10	Low	HVAC (Water side)	Pump head computation
11	High	HVAC (Air side)	Schedule of Air Side Equipment (FCU/AHU/DX) (indicating quantity, location and operation mode)
12	High	HVAC (Air side)	Drawings showing the schematic, layout and control of building cooling system (air side)
13	Medium	HVAC (Air side)	AHU/PAU/FCU Fan Motor Technical Specification
14	High	Lighting	Lighting layout plan
15	Medium	Lighting	Lighting schedule (indicating quantity, location, type of luminaire, illuminance target)
16	High	Lighting	Computation of light power density
17	Low	Lighting	Technical product information of lighting luminaries
18	Low	Domestic water	Schedule of Ancillary Pumps and Nameplate Motor
19	Medium	Mechanical ventilation	Drawings showing the schematic, layout and control of mechanical ventilation system (motion, occupant, CO)
20	Medium	Mechanical ventilation	Technical specification of equipment (MV fan)

21	Medium	Lift / Escalator	Technical product information of lifts and escalators (VVVF or regenerative motor drive, sleep mode)
22	Medium	Renewable sources	PV solar, wind, rain water harvesting (installed capacity, annual generation)
23	Medium	Energy efficient features	Heat recovery devices, sun pipes, light shelves, demand controlled using sensors (motion, occupant, photo, CO, CO2)

Dynamic Parameters			
Item	Priority	Part	Item
24	High	Internal Gains	Room setpoints (and other operation controls e.g., daylight/motion sensors)
25	Medium	Internal Gains	Internal Gains or specific room sub meter reading (Equipment/Computers/etc)
26	High	HVAC (Water side)	Chilled Water / Air Cooled Plant control strategy
27	High	HVAC (Air side)	AHU FCU control strategy and operation hours
28	Low	Internal Gains	Lighting Operation Profile
29	Medium	Internal Gains	Equipment Operation Profile
30	Medium	Internal Gains	Occupancy Profile

Measured Calibration Parameters			
Item	Priority	Part	Item
31	High	HVAC (M&V / BMS / BAS)	Operating data of chiller plant at 1 minute interval for 1 week (RT, L/s, °C, kW, kWh)
32	High	HVAC (M&V / BMS / BAS)	Latest chiller plant audit report (annual Operating System Efficiency Report)
33	High	Utilities	Monthly electricity bills with tariff mechanism - peak / odd peak, contracted / uncontracted capacity) for last three years
34	High	Utilities	Electricity consumption profile at half hour interval for last three years
35	Medium	Utilities	Electricity consumption record (automatic / manual) of individual system (chiller plant, air distribution, lighting, lift, receptacle, etc)
36	High	HVAC (Water side)	Total building cooling load profile in a week
37	Low	HVAC (M&V / BMS / BAS)	Computation of the overall uncertainty of measurement of chiller plant efficiency
38	Medium	Utilities	Monthly water bills for last three years
39	Medium	Utilities	Water consumption record (automatic / manual) of individual system (cooling tower, irrigation, toilet, etc)