AI for Solar Farms

Insights & Decision-making

R&B Technology (USA) Company, Inc.

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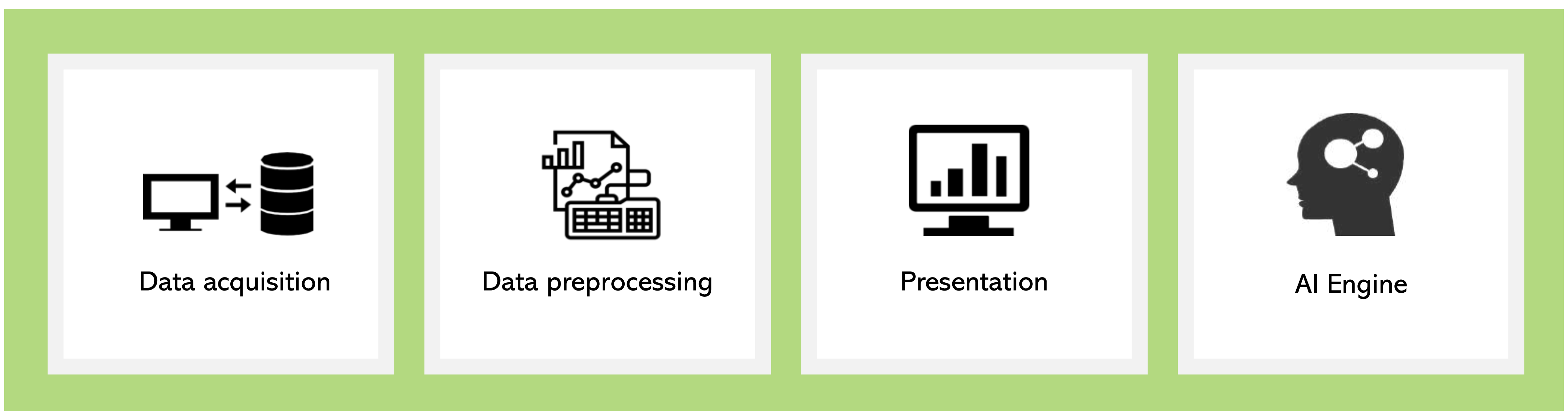
R&B at a Glance

Brief introduction

- R&B Technology registered in
  - Sugar Land, Texas, USA
- Artificial Intelligence (AI) technology
- Global presence
- Pioneer in the use of AI for property management

- R&B's solution, **AdOPT AI**, is a cloud-based software platform powered by a powerful
  AI Engine. The platform's analytics delivers actionable recommendations by acquiring and analyzing data from various databases and data feeds.



Issues for Operations Management

Workforce

Extreme shortage of professionals to execute O&M and Optimization

Domain Expertise

Lack of control decision transparency and shortage of domain expertise

Software Tools

Difficult to use and capabilities not able to identify root causes or conduct commissioning

Multi-dimensional & nonlinear problems

Interactions too complicated to be identified by rules

Patterns & data characteristics difficult to identify with traditional tools

Domain knowledge alone can't identify masked relationships

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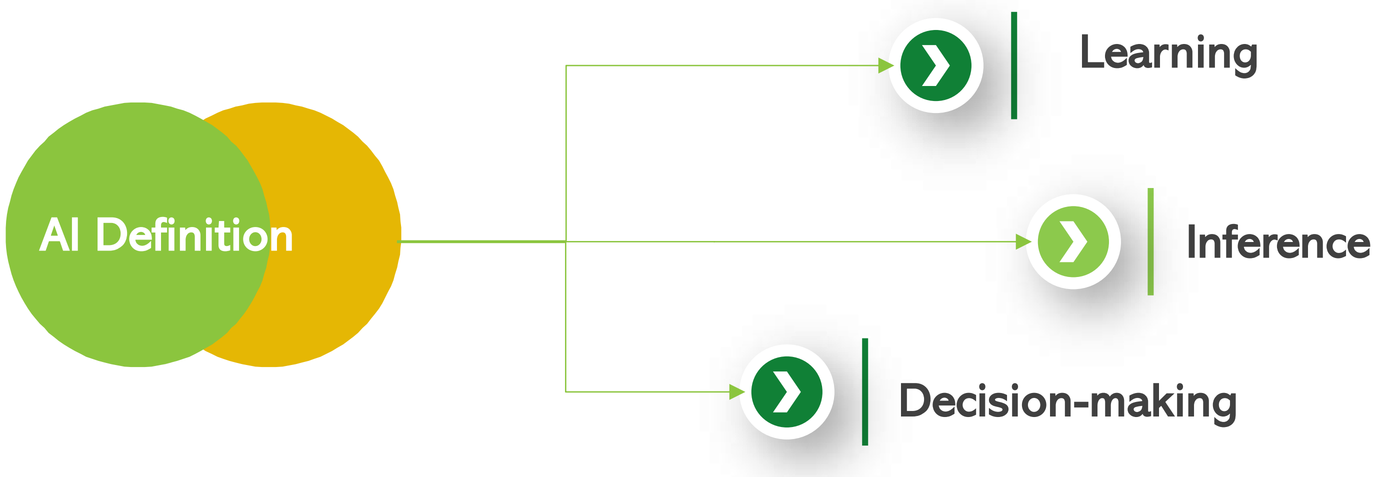
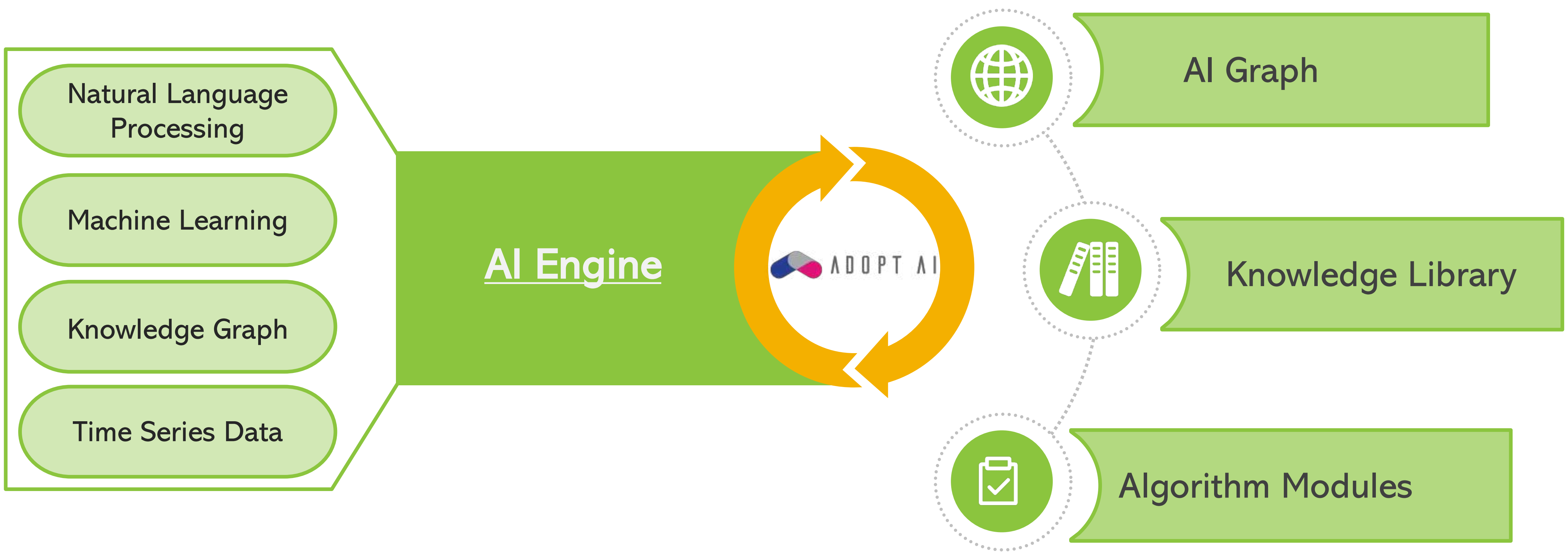
BeOP's AI Engine





How AdOPT AI Engine Learns & Generates Knowledge

- Carefully designed and developed, AdOPT AI Engine significantly reduces reliance on human expertise in various applications.

Raw Data

Labelling

Minimal human interference with domain knowledge

Pre-Processing

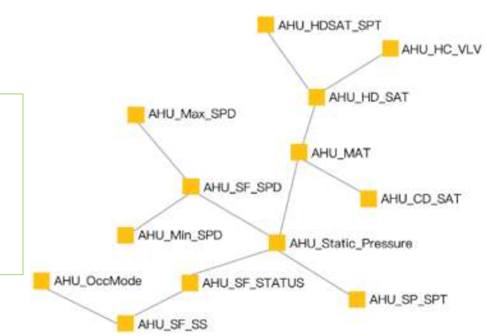
Knowledge library

8000+ rules

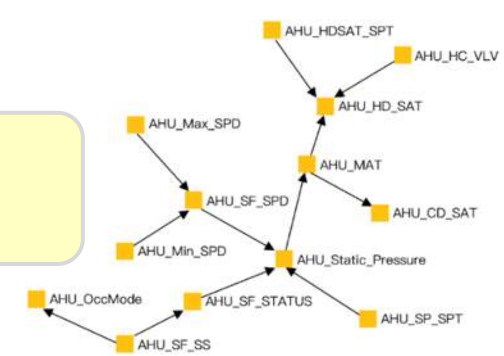
AI Graph

Algorithm Modules

*Extracted **object network** from data*



*Automatically generated **knowledge graph** after labelling*



Applications

Fault Detection & Diagnostics

Optimization

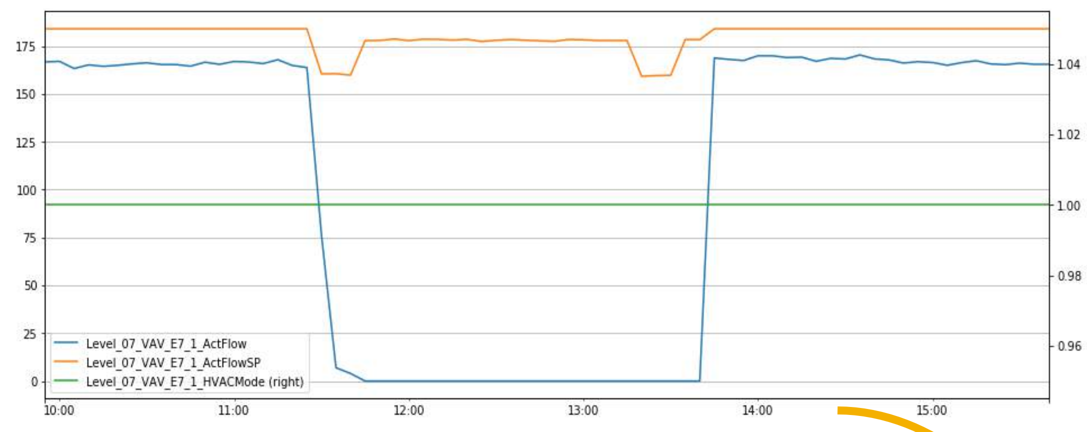
Deep Inference

Failure Prediction

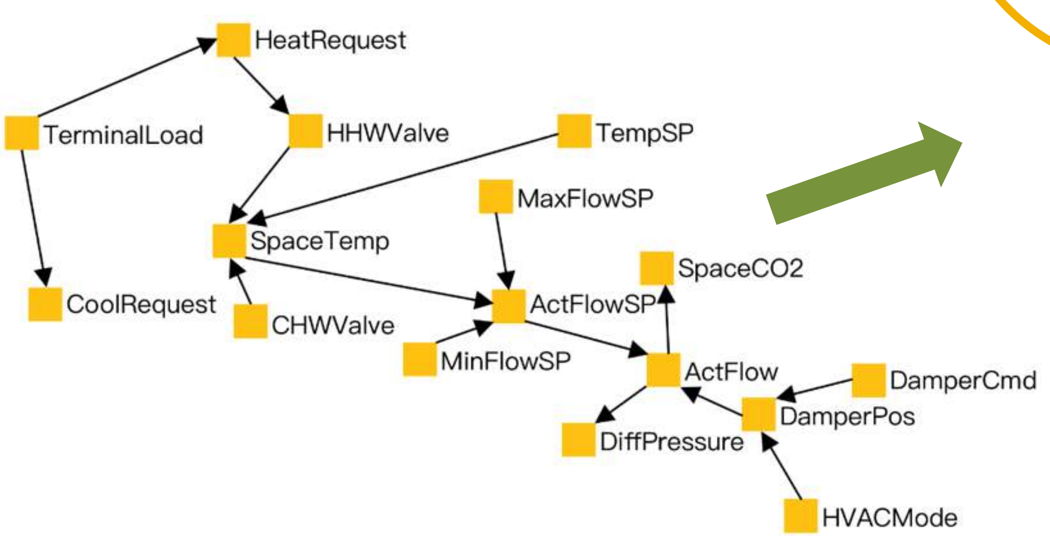
A Revolutionary Methodology of FDD

Use case: Significant deviation of VAV airflow from set point

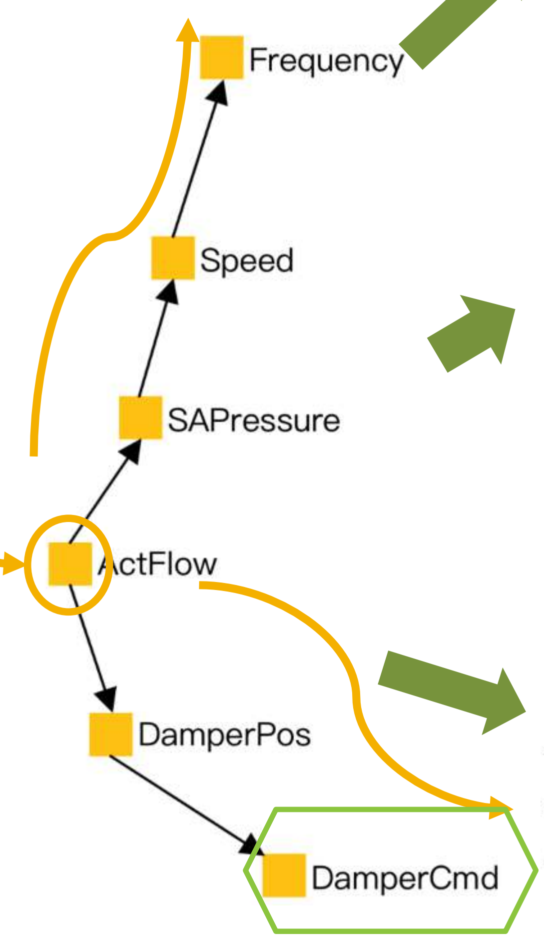
1. Autonomously learning patterns of control threshold

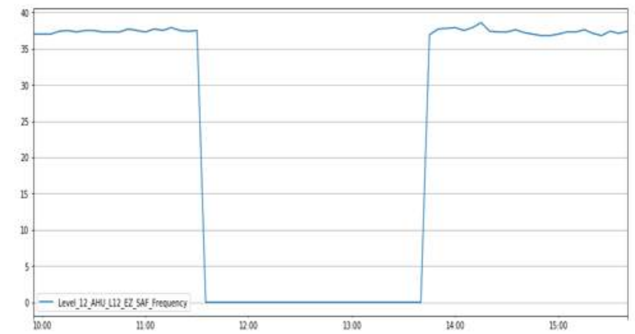


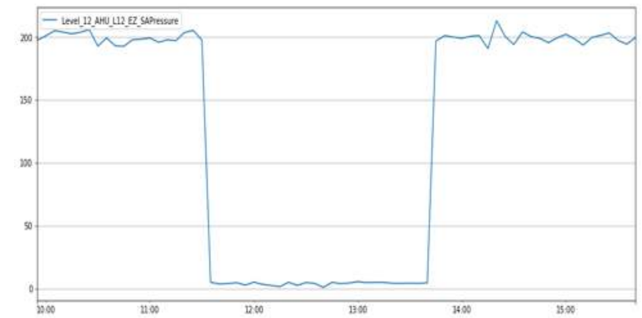
2. Autonomously learning and generating AI graph



3. Deep inference over network paths to identify the root cause – abnormal fan speed







4. Knowledge extraction

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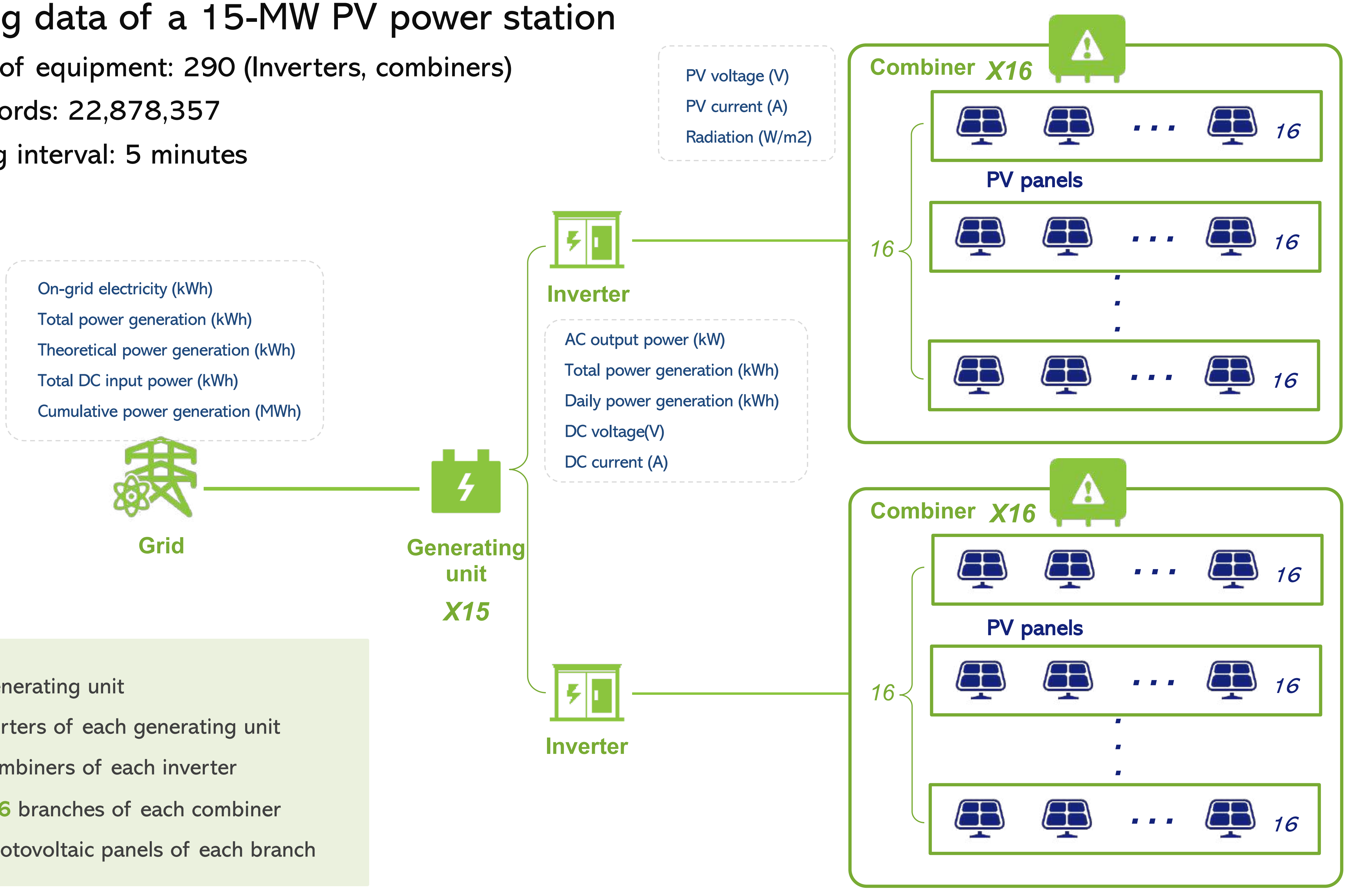
[('Level_07_VAV_E7_1_DamperPos<=73.97', False),
 ('Level_12_AHU_L12_EZ_SAPressure<=170.422', True),
 ('Level_07_VAV_E7_1_ActFlowSP<=134.0', False),
 ({'high': 0.204, 'low': 0.597, 'medium': 0.199}, 196.0)]
```

CONTENTS

A Case Study of AI-driven Analytics in Utility-level Solar Farm

Operating data of a 15-MW PV power station

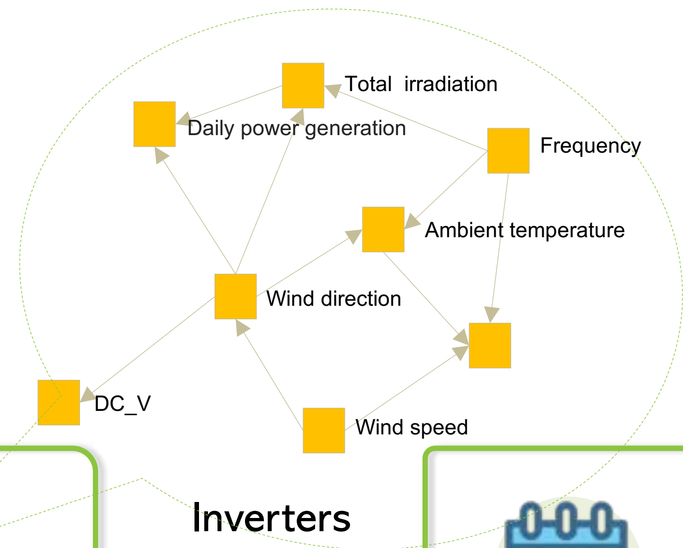
- Amount of equipment: 290 (Inverters, combiners)
- Data records: 22,878,357
- Sampling interval: 5 minutes

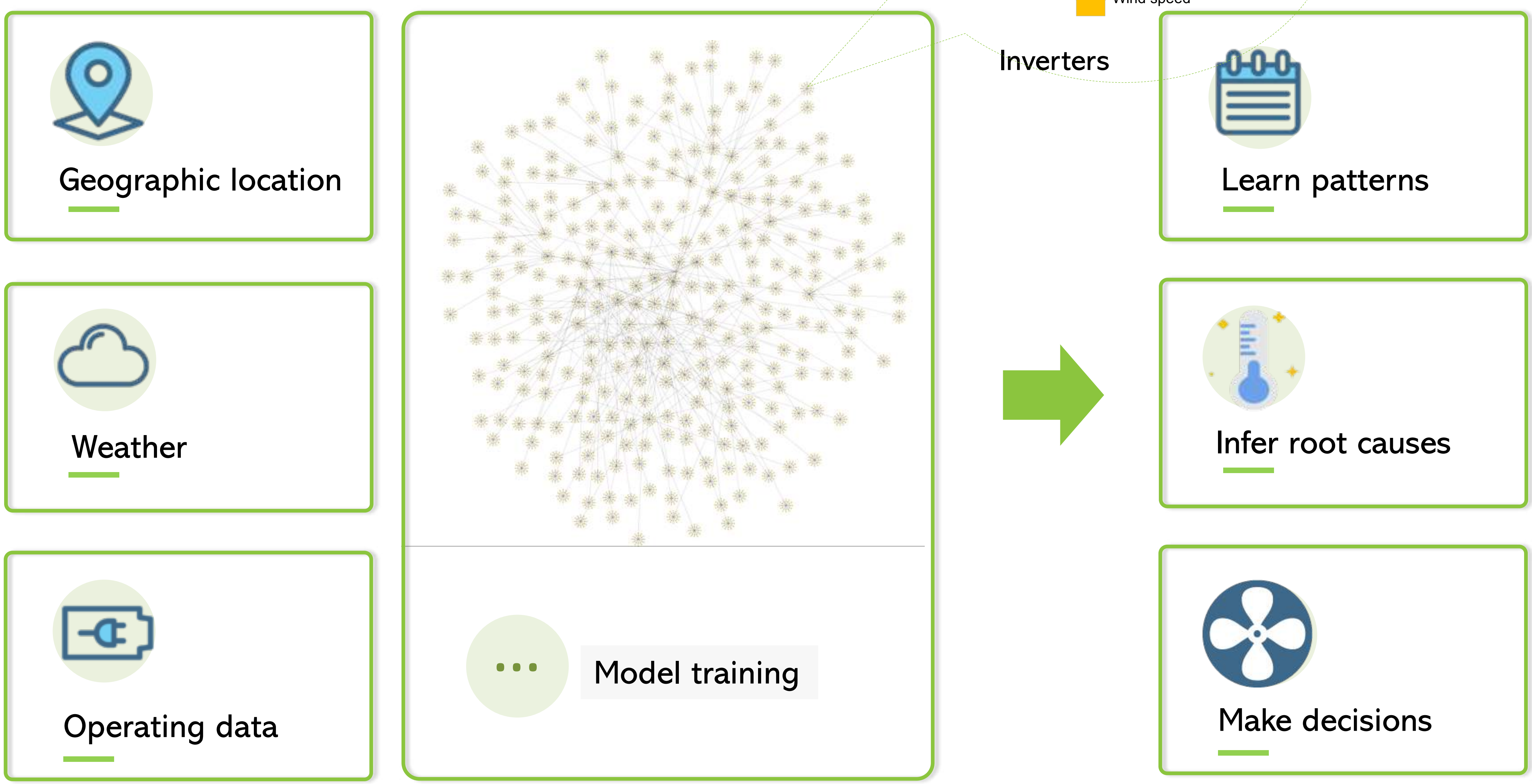


- 15 Generating unit
- 2 Inverters of each generating unit
- 16 combiners of each inverter
- 14~16 branches of each combiner
- 16 Photovoltaic panels of each branch

AI Graph for the Solar Farm

- AI detects abnormalities of every piece of equipment which is modelled with machine learning.
- AI makes decisions on root causes over the graph that is modelled with historical data.

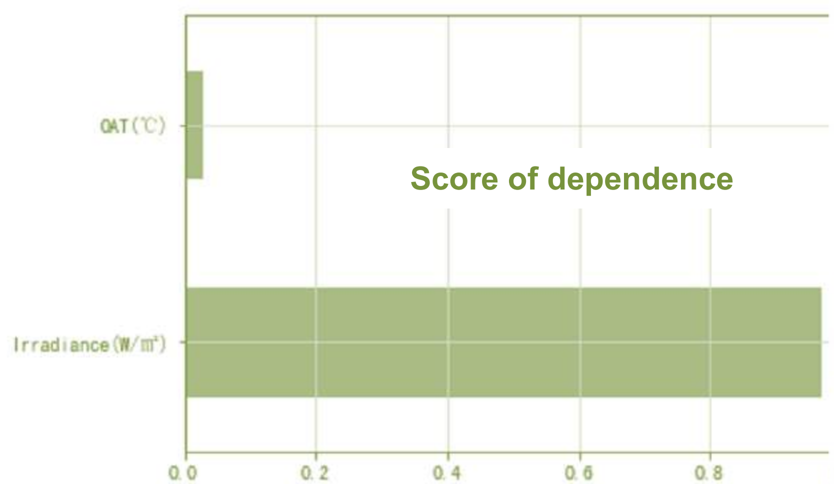


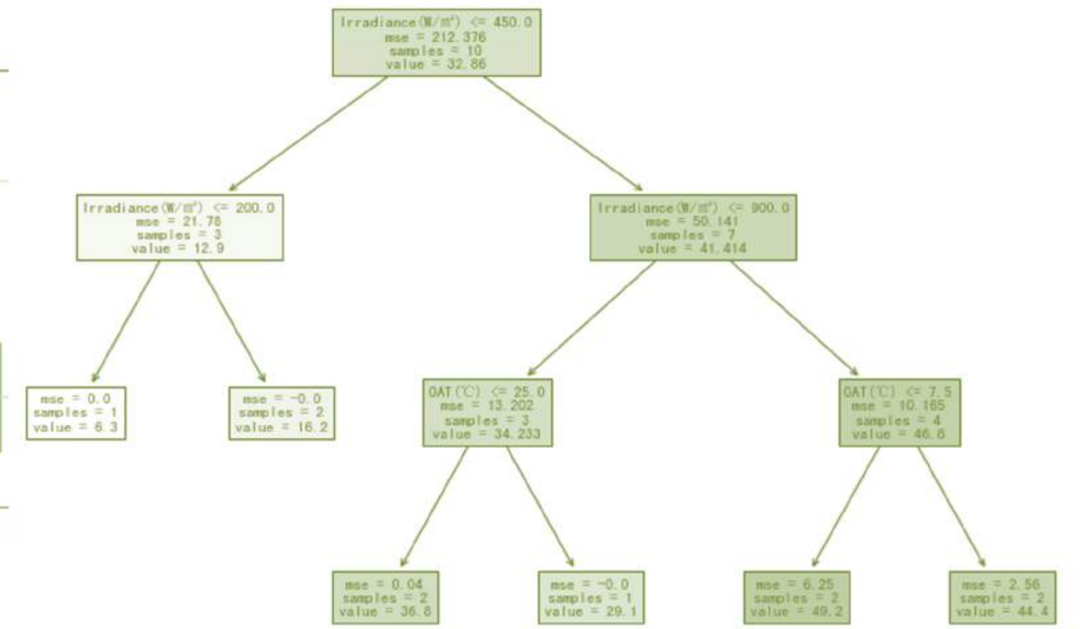


How AI Makes Decisions?

Raw Data → AI learns patterns in terms of distribution, dependence, and time-series feature. → AI decision-making process

Radiation (W/㎡)	Ambient T (℃)	Power (kW)
600	-10	30.7
100	15	7.2
1000	10	47.5
1000	25	44.2
800	35	36.7
1000	-10	47.5
100	10	7.2
800	25	37.6
1200	15	56.2
1000	35	40.9
800	10	37.6
1200	30	47.9
1200	25	52.9
600	10	30.7
1200	0	56.2
800	15	37.6
600	30	30.7
100	-10	7.2
1200	-10	56.2
100	20	7.2





The higher the solar radiation and the lower the ambient temperature, the more power generated

Proof of Concept of AI-powered Abilities

Significant Increase in Net Cash Flow

↑

FDD	Prediction	Analysis
◆ Fault and abnormality detection ◆ Push alerts and automatic reporting	◆ Generation ability ◆ Generation loss ◆ Dirt prediction on modules ◆ Auxiliary Power analysis	◆ Equipment availability ◆ Generation efficiency ◆ Equipment performance

AI Engine

01

Fault Detection & Diagnostics

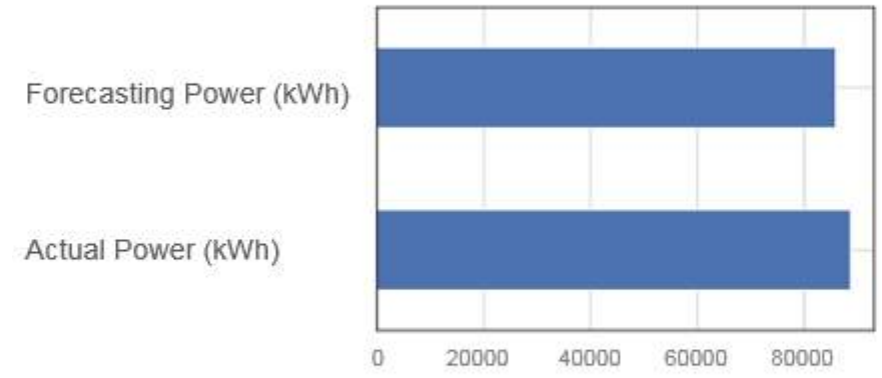
Powered by AI Engine

Fault Detection & Diagnostics

Fault Detection

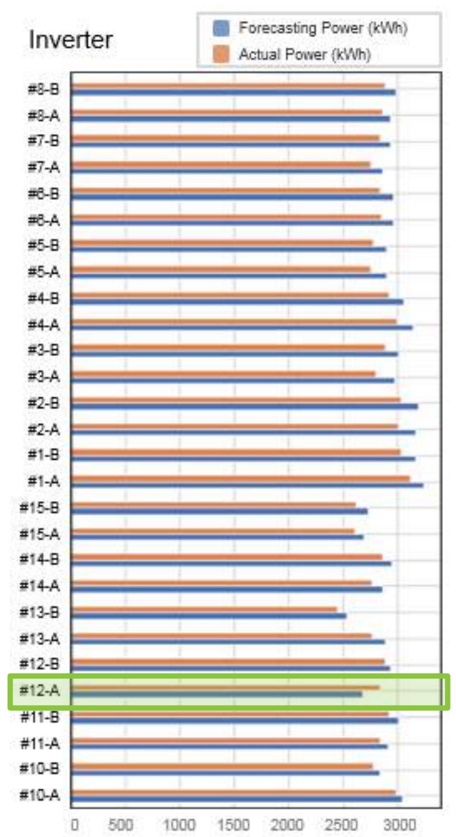
1. Sensor FDD
2. Equipment FDD
3. Power generation performance diagnostics

Power generation correlation analysis and fault detection



- AI runs FDD for each inverter and combiner
- AI trained with data sets comprising of multi-variables such as temperature, radiation, time, etc.
- Comparison actual performance of each device and system to predicted performance

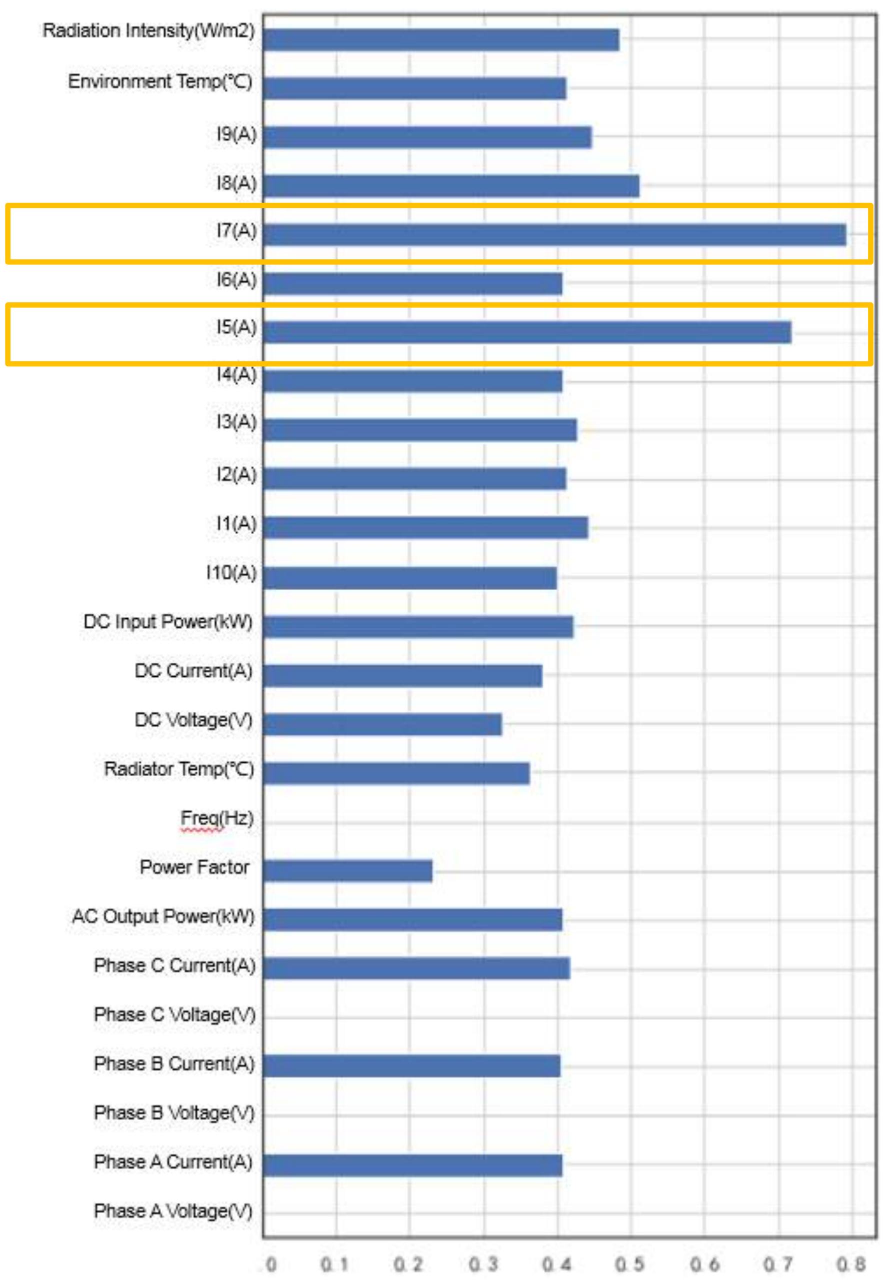
Detection of Low Amps at Inverters



#12_A_Inverter: Actual power generation is abnormally low

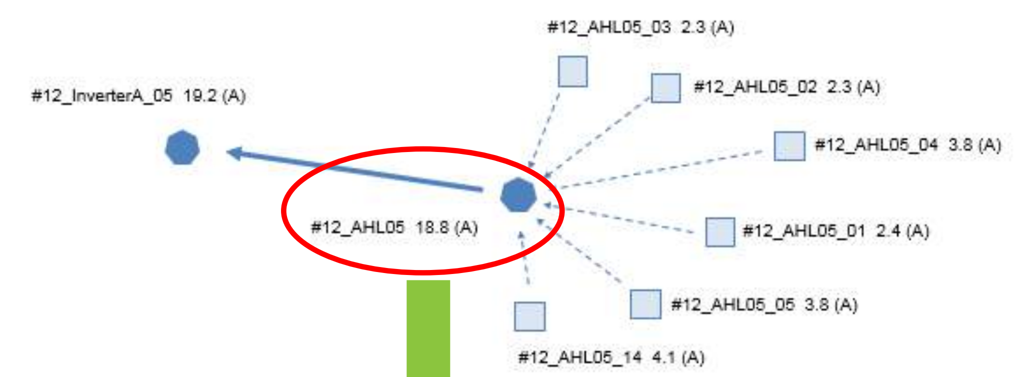
Junction Box	Actual(kWh)	Prediction(kWh)	Error(%)
12AHL07	118.4	216.0	82.5
12AHL05	273.9	382.7	39.7
12AHL03	323.5	321.0	-0.8
12AHL02	387.8	379.3	-2.2
12AHL04	413.2	402.3	-2.6
12AHL06	255.9	248.6	-2.9
12AHL09	276.3	267.5	-3.2
12AHL08	406.4	390.6	-3.9
12AHL01	363.3	346.0	-4.8

Power generation of some junction boxes is abnormally low

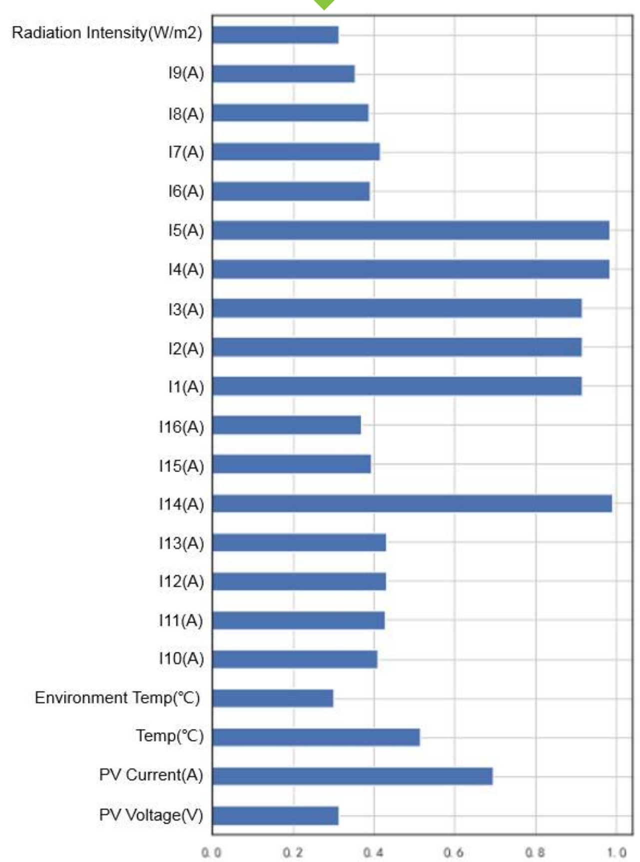


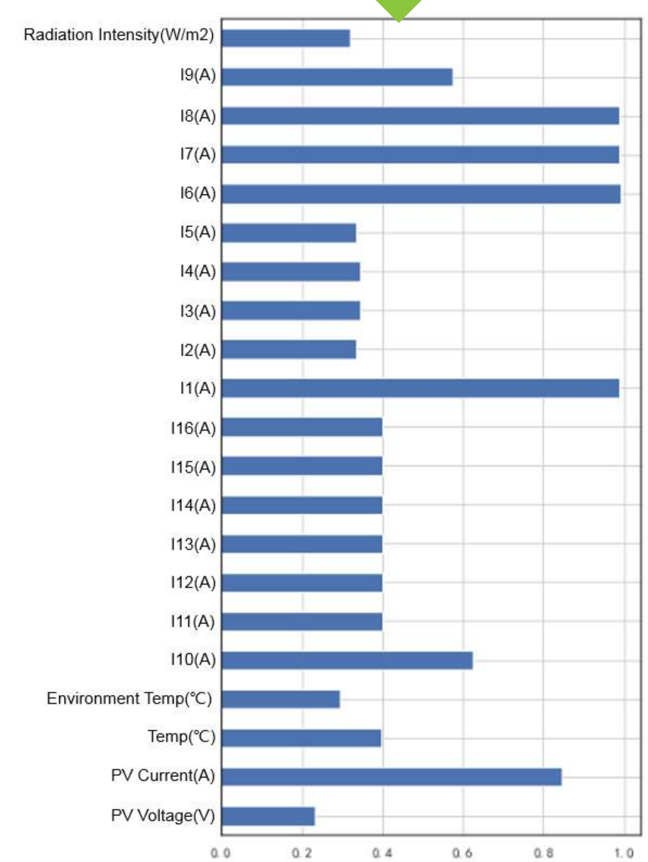
#12_A_Inverter anomaly index : The current value of circuit 05 and 07 is abnormally low

Inference of Detected Low Amps at Junction Box



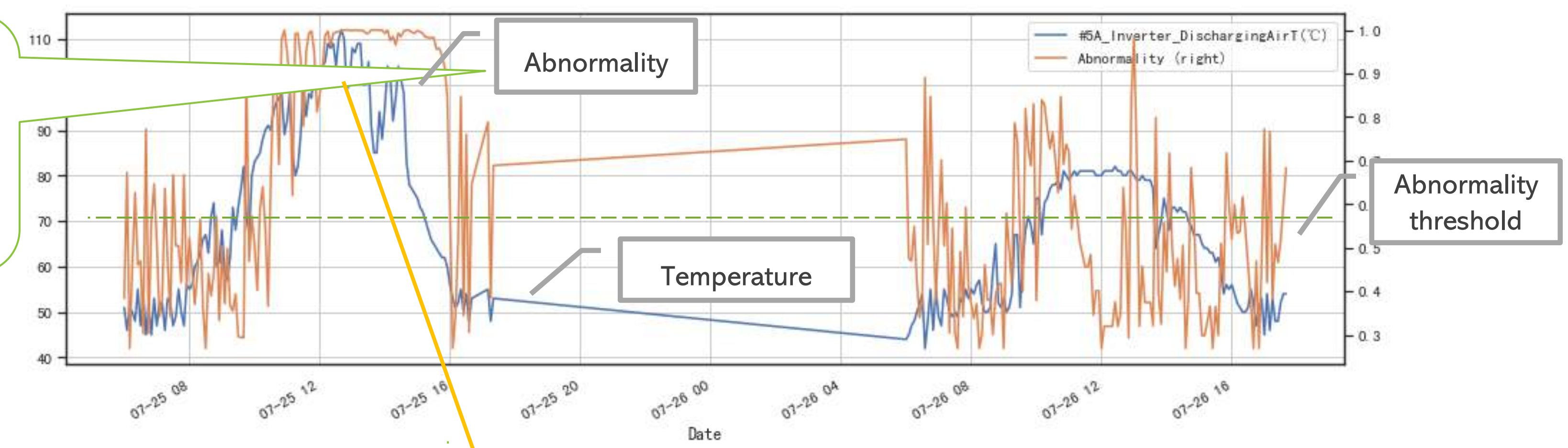
Root cause tracing: current of 12_AHL_07 and 12_AHL_05 combiners is abnormally small

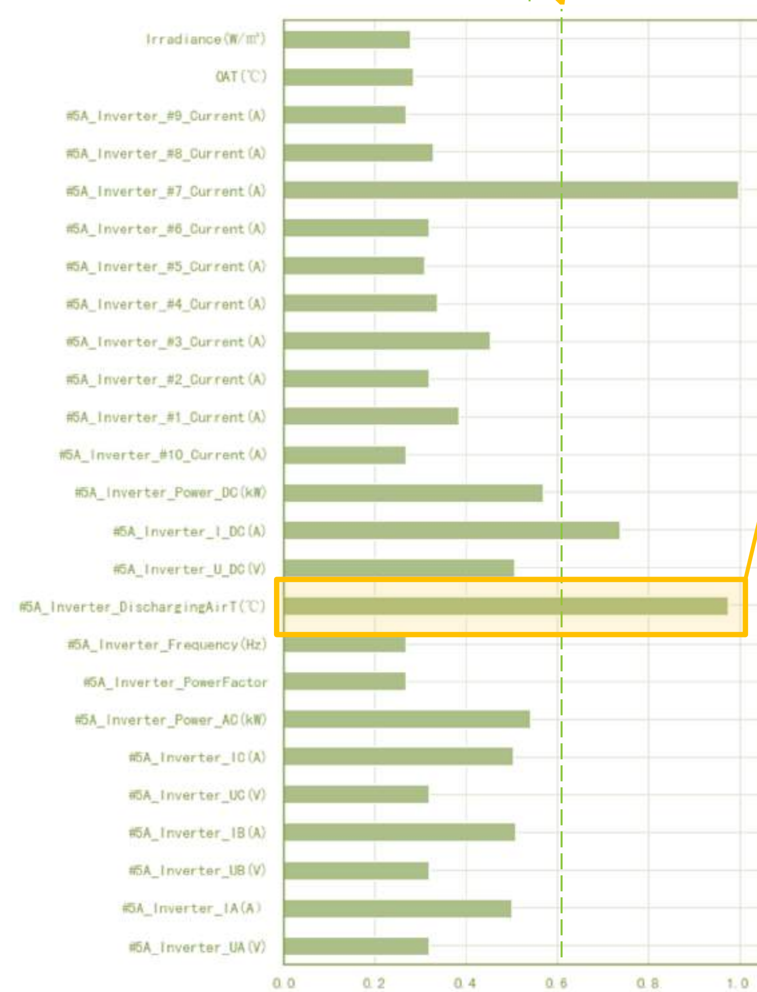




Detection of Abnormal Operation of an Inverter Fan

AI detects the abnormality score exceeds the threshold on July 25, 2019.





	high_bound	low_bound	score	2019-07-25 12:00:00
#5A_Inverter_UA(V)	157.87	145.13	0.32	150.00
#5A_Inverter_IA(A)	776.76	685.24	0.50	685.00
#5A_Inverter_UB(V)	157.86	145.14	0.32	150.00
#5A_Inverter_IB(A)	796.24	702.76	0.51	701.00
#5A_Inverter_UC(V)	156.82	144.18	0.32	149.00
#5A_Inverter_IC(A)	792.51	699.49	0.50	699.00
#5A_Inverter_Power_AC(kW)	357.61	315.39	0.54	312.00
#5A_Inverter_PowerFactor	1.04	0.96	0.27	1.00
#5A_Inverter_Frequency(Hz)	52.00	48.00	0.27	50.00
#5A_Inverter_DischargingAirT(°C)	**84.59**	**76.41**	**0.98**	**100.00**
#5A_Inverter_U_DC(V)	484.51	442.49	0.51	485.00
#5A_Inverter_I_DC(A)	834.09	737.91	0.74	688.00
#5A_Inverter_Power_DC(kW)	385.77	340.23	0.57	334.00
#5A_Inverter_#10_Current(A)	0.00	-0.00	0.27	0.00
#5A_Inverter_#1_Current(A)	125.55	111.25	0.38	114.60
#5A_Inverter_#2_Current(A)	99.25	87.85	0.32	94.90
#5A_Inverter_#3_Current(A)	114.23	101.17	0.45	102.40
#5A_Inverter_#4_Current(A)	101.12	89.48	0.34	93.40
#5A_Inverter_#5_Current(A)	106.18	93.92	0.31	98.90
#5A_Inverter_#6_Current(A)	104.34	92.26	0.32	96.90
#5A_Inverter_#7_Current(A)	112.60	99.70	1.00	52.00
#5A_Inverter_#8_Current(A)	83.39	73.71	0.33	77.20
#5A_Inverter_#9_Current(A)	0.00	-0.00	0.27	0.00
OAT(°C)	35.32	31.38	0.28	33.50
Irradiance(W/㎡)	949.46	839.02	0.28	896.34

Features

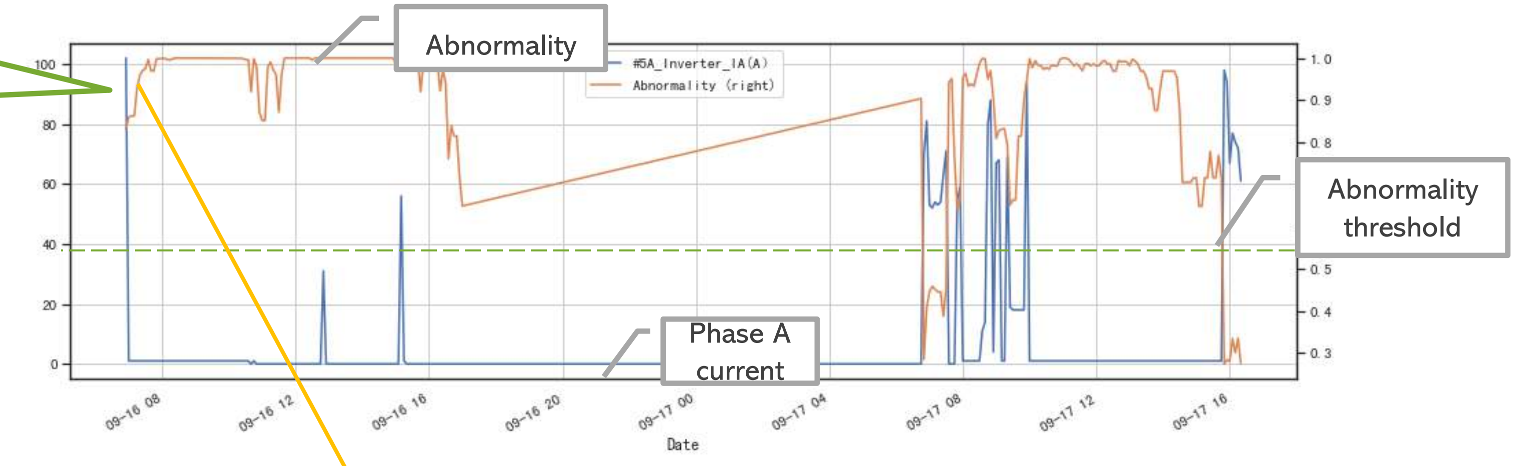
- Communication normal
- Heat exchanger overheat

Probable cause

- The fan doesn't work properly

Detection of Abnormal IGBT

AI detects imbalance between phase A and phase B current at 7am Sep. 16, 2019.

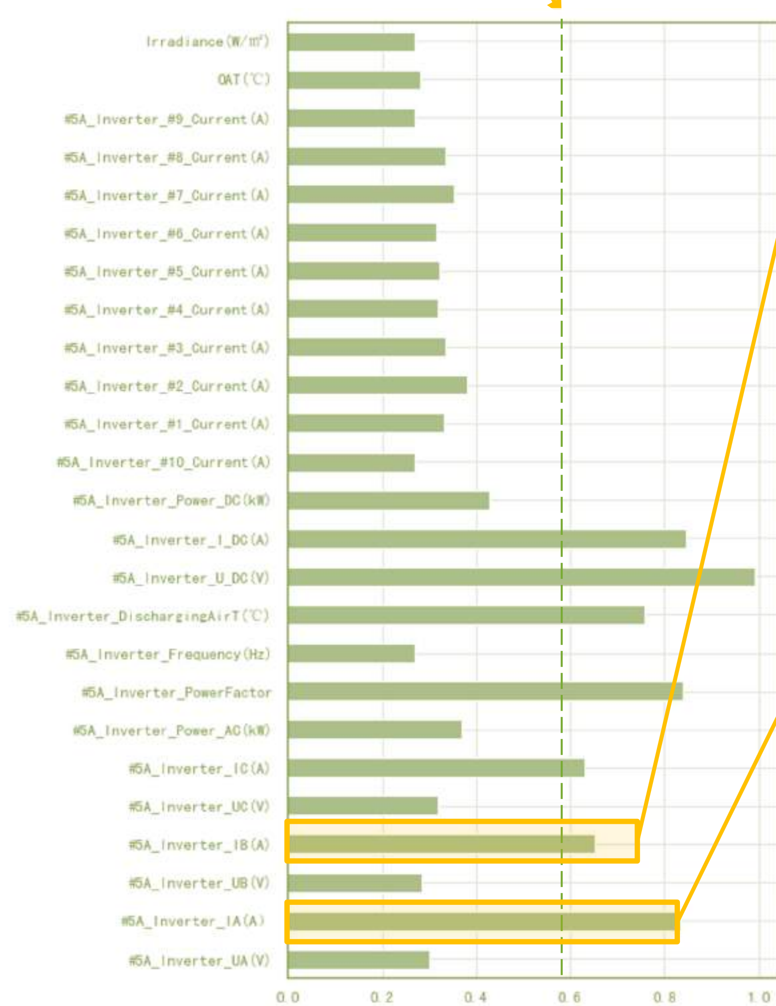


Features

- Communication feature
- Abnormal current with phase A and B
- The abnormality continues for quite a while

Probable cause

- Abnormal IGBT



	high_bound	low_bound	score	2019-09-16 06:55:00
#5A_Inverter_UA(V)	157.35	144.65	0.30	150.00
#5A_Inverter_IA(A)	72.16	34.84	0.83	102.00
#5A_Inverter_UB(V)	157.86	145.14	0.28	151.00
#5A_Inverter_IB(A)	73.96	36.04	0.65	24.00
#5A_Inverter_UC(V)	156.82	144.18	0.32	149.00
#5A_Inverter_IC(A)	73.87	36.13	0.63	84.00
#5A_Inverter_Power_AC(kW)	32.61	15.39	0.37	28.00
#5A_Inverter_PowerFactor	1.03	0.95	0.84	0.89
#5A_Inverter_Frequency(Hz)	52.00	48.00	0.27	50.00
#5A_Inverter_DischargingAirT(℃)	50.79	45.21	0.76	54.00
#5A_Inverter_U_DC(V)	540.67	494.33	0.99	654.00
#5A_Inverter_I_DC(A)	69.17	31.83	0.85	0.00
#5A_Inverter_Power_DC(kW)	33.73	15.27	0.43	31.00
#5A_Inverter_#10_Current(A)	0.00	-0.00	0.27	0.00
#5A_Inverter_#1_Current(A)	10.53	5.07	0.33	8.60
#5A_Inverter_#2_Current(A)	8.46	4.04	0.38	7.40
#5A_Inverter_#3_Current(A)	9.92	4.88	0.34	8.20
#5A_Inverter_#4_Current(A)	8.72	4.18	0.32	7.00
#5A_Inverter_#5_Current(A)	9.20	4.40	0.32	7.40
#5A_Inverter_#6_Current(A)	8.82	4.08	0.32	7.00
#5A_Inverter_#7_Current(A)	10.11	5.09	0.35	8.60
#5A_Inverter_#8_Current(A)	7.21	3.39	0.33	5.90
#5A_Inverter_#9_Current(A)	0.00	-0.00	0.27	0.00
OAT(℃)	20.81	17.99	0.28	19.30
Irradiance(W/㎡)	78.14	34.73	0.27	56.26

02

Prediction

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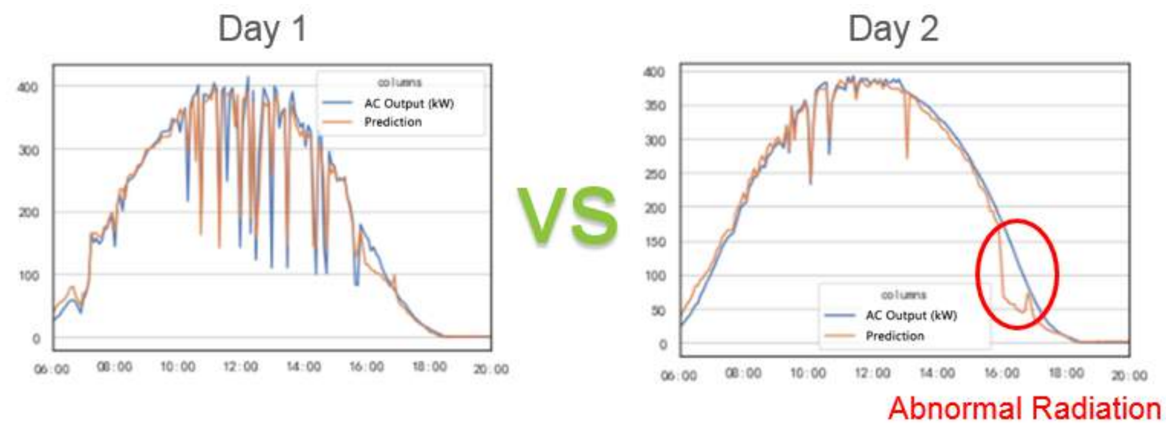
Performance Analysis & Prediction

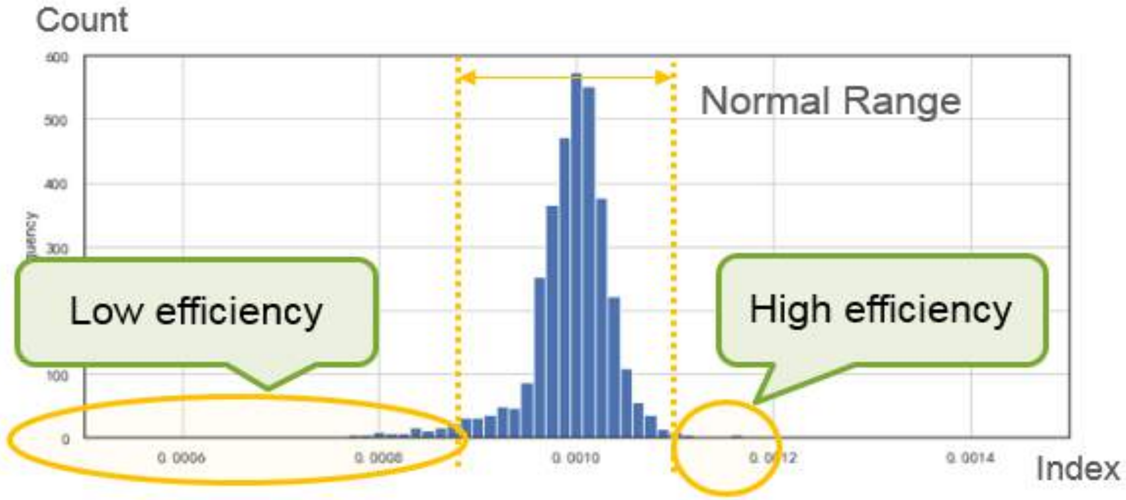
Performance Prediction

1. Performance Impact Factor
2. Performance Index Analysis
3. Correlation Analysis
4. Performance Prediction

Performance Impact Factor: Abnormal radiation of inverter at the 8th zone A



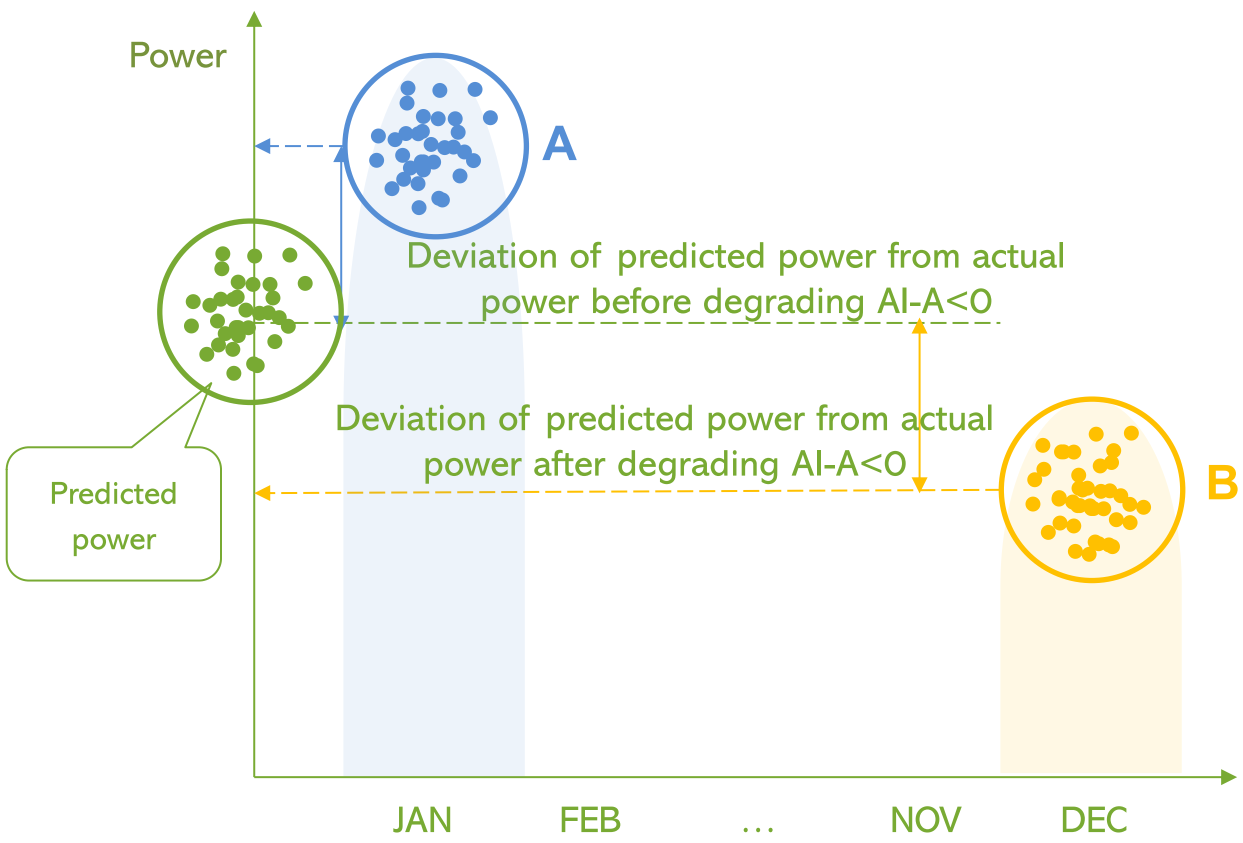
Performance Index Analysis: Low efficiency of inverter at the 10th zone A



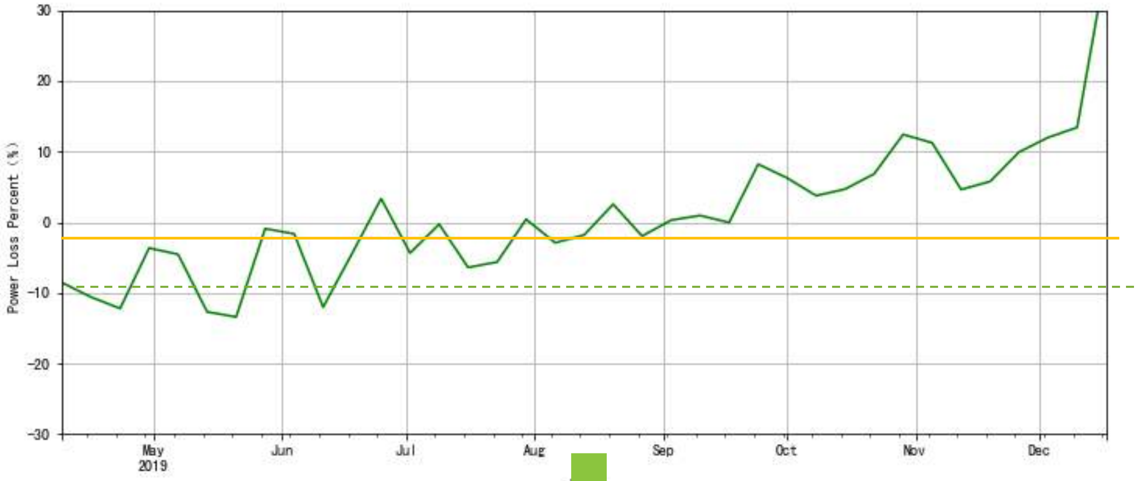
Prediction on Performance Degrading & Dirt Cleaning

Predictive generation model by AI

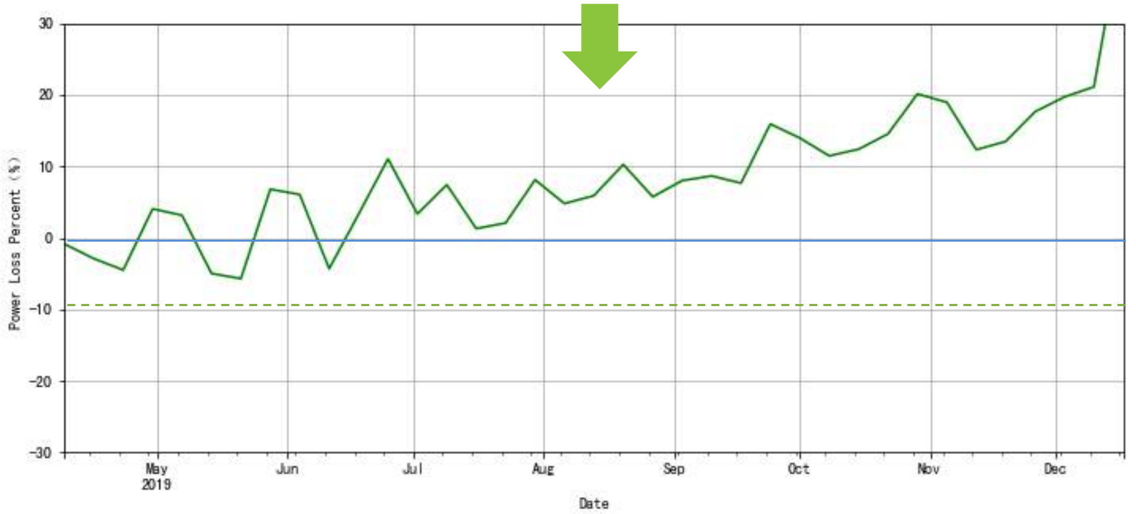
Mostly ambient temperature and solar radiation as input to predict power generation



How much actual generated power deviates from prediction?

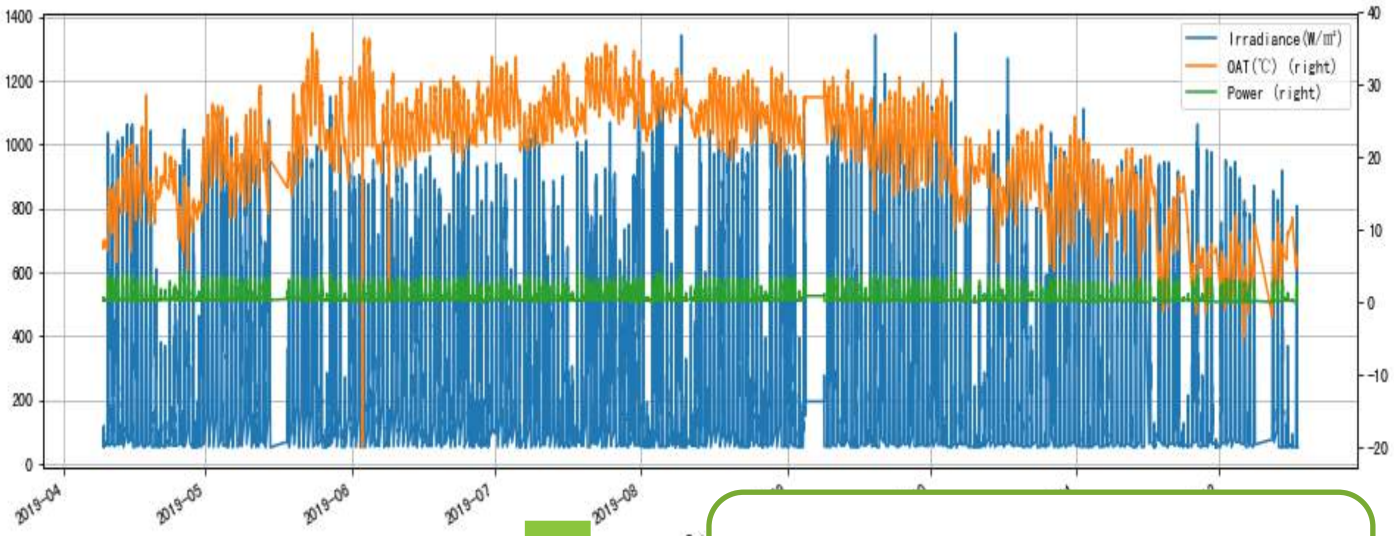


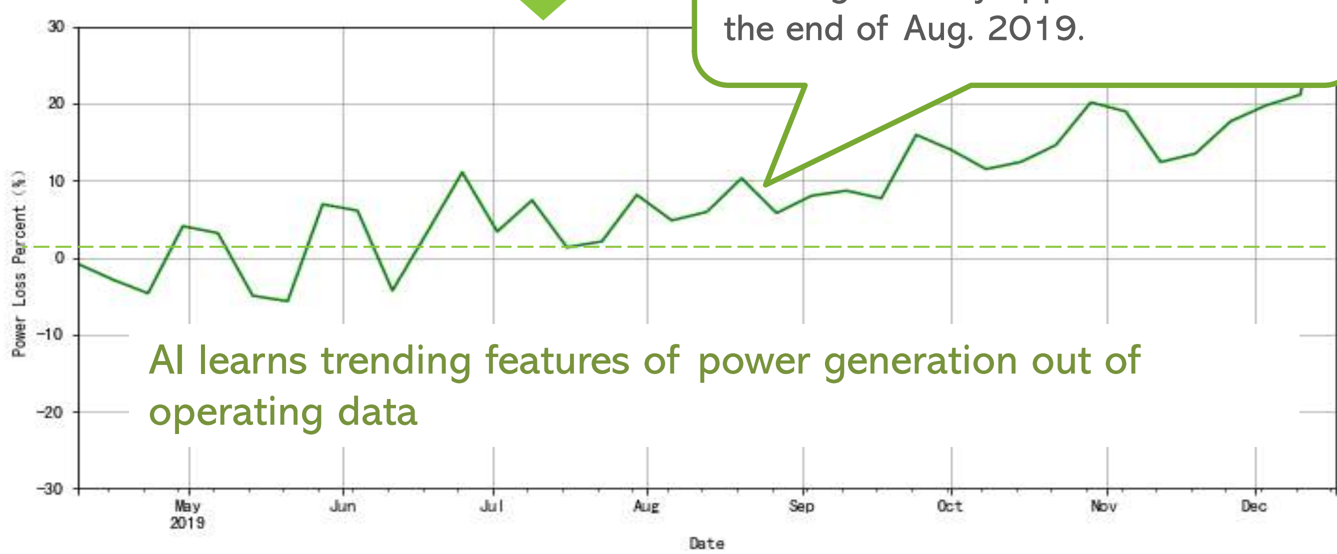
Generation degrading % curve after offset



Power Loss due to Generation Degrading (at Modules)

- Predicted power loss of #14 circuit of 7AHL07 junction box due to degrading from Mar 25 to Dec 17.

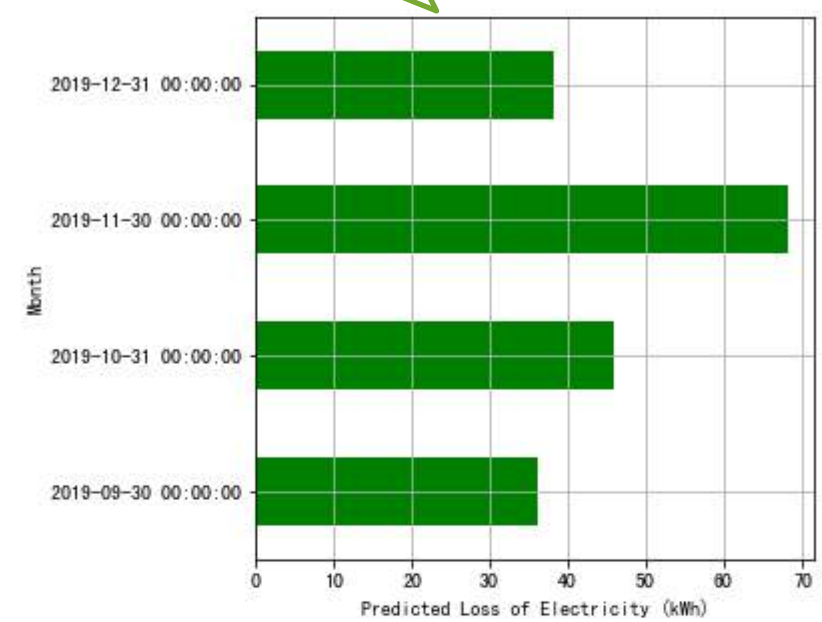




AI detects generation of this module has degraded by approx. 10% since the end of Aug. 2019.

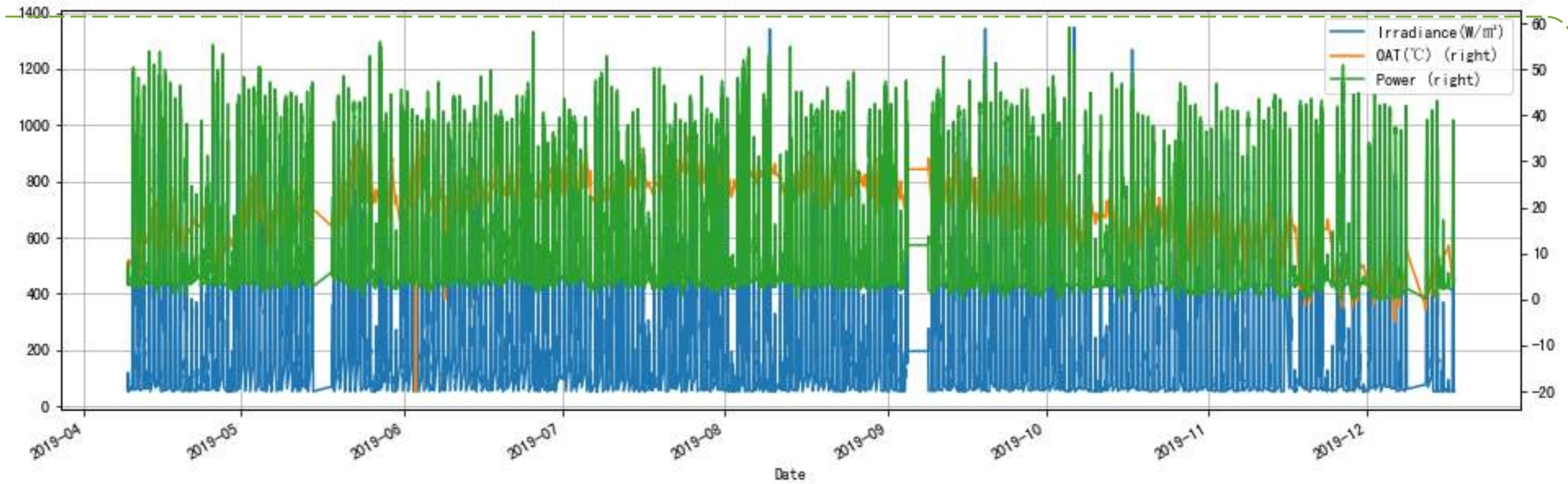
AI learns trending features of power generation out of operating data

If it were cleaned at the end of Aug., up to **188kWh** would have been added to power generation, equivalent to **13%** of total power this single circuit generated in 4 months.



Power Loss due to Generation Degrading (at Junction Box)

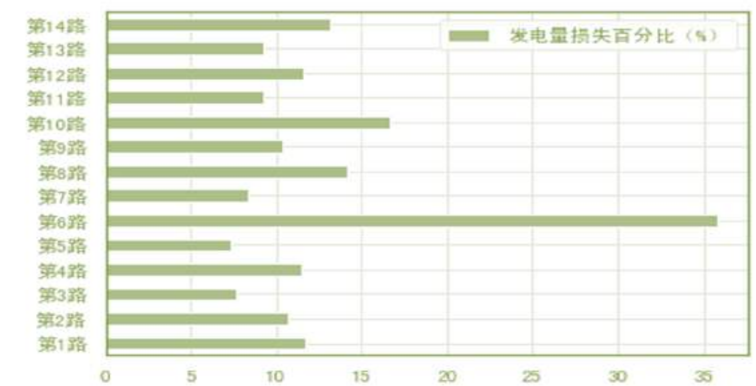
- Predicted power loss of all circuits of 7AHL07 junction box due to degrading from Mar 25 to Dec 17.



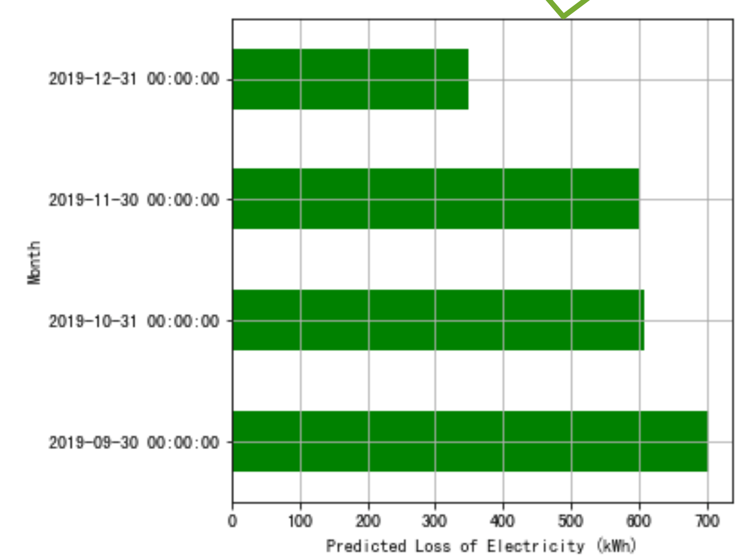
AI detects generation of this module has degraded by approx. 10% since the end of Aug. 2019.

AI learns trending features of power generation out of operating data

% power loss of each circuit of 7AHL07 junction box with median value 11%。



If it were cleaned at the end of Aug., up to **2263kWh** would have been added to power generation, equivalent to **11.4%** of total power this junction box generated in 4 months.

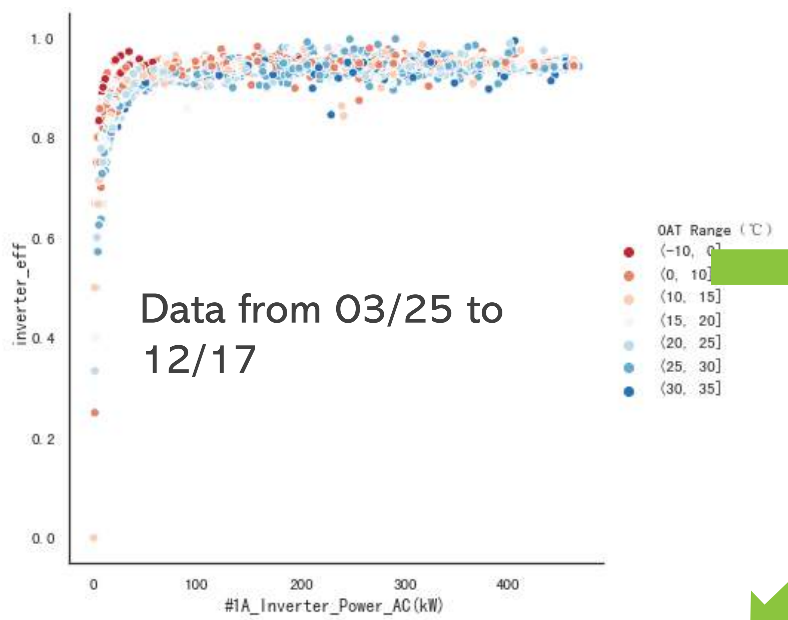


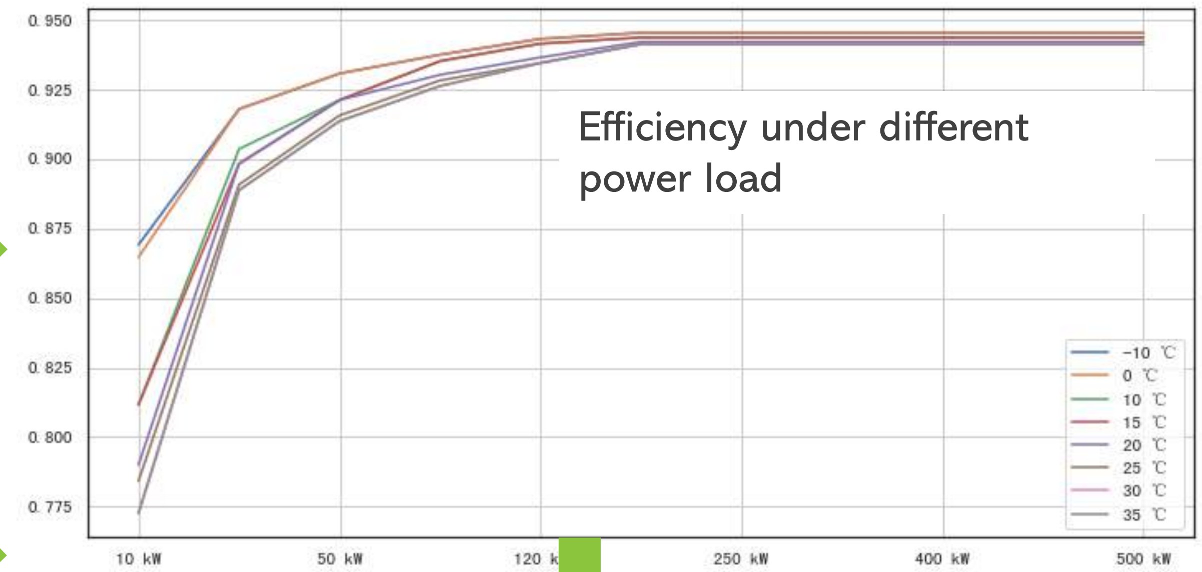
03

Analysis

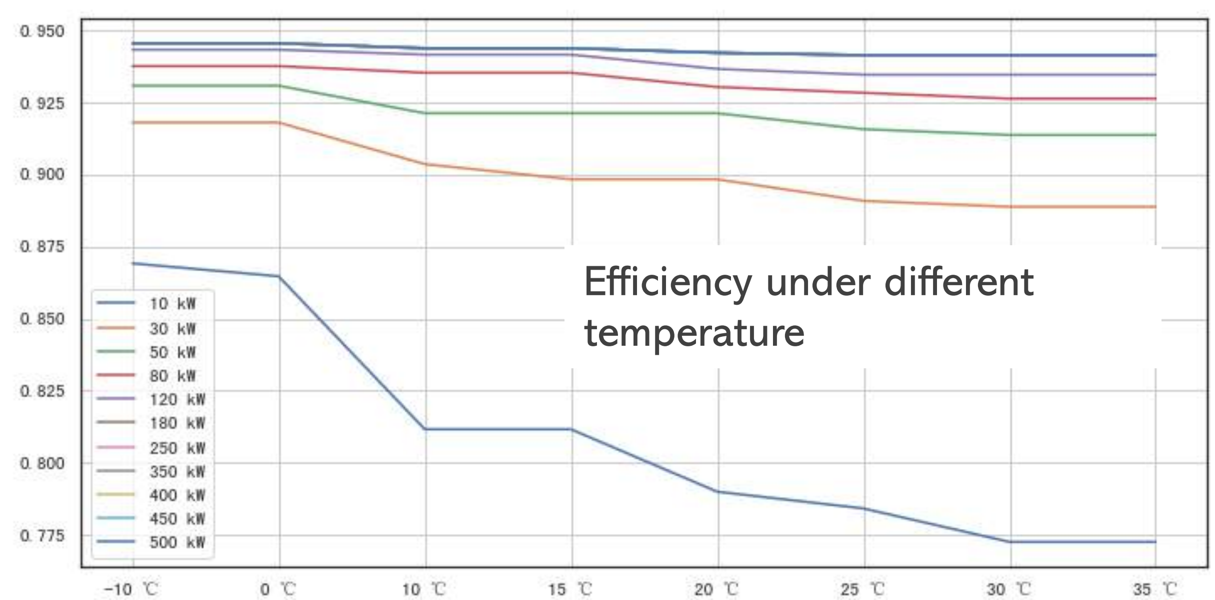
Powered by AI Engine

Performance Models of Inverters



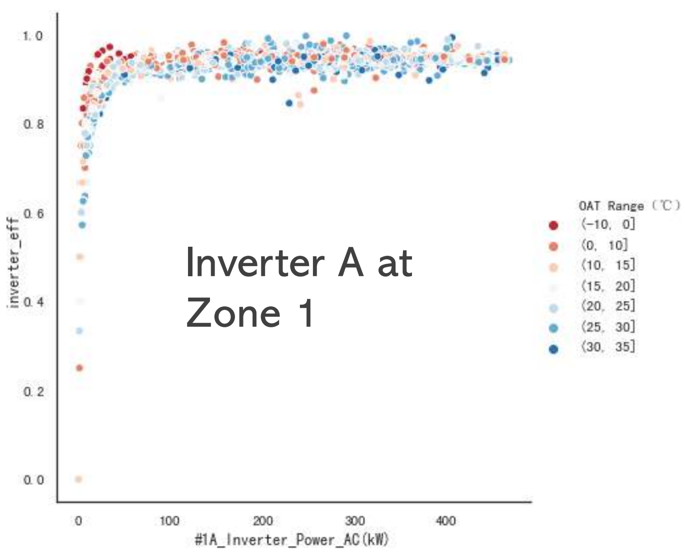


	-10 ℃	0 ℃	10 ℃	15 ℃	20 ℃	25 ℃	30 ℃	35 ℃
10 kW	0.869	0.865	0.812	0.812	0.790	0.784	0.773	0.773
30 kW	0.918	0.918	0.904	0.898	0.898	0.891	0.889	0.889
50 kW	0.931	0.931	0.921	0.921	0.921	0.916	0.914	0.914
80 kW	0.938	0.938	0.935	0.935	0.930	0.928	0.926	0.926
120 kW	0.943	0.943	0.941	0.941	0.937	0.935	0.935	0.935
180 kW	0.945	0.945	0.944	0.944	0.942	0.941	0.941	0.941
250 kW	0.945	0.945	0.944	0.944	0.942	0.941	0.941	0.941
350 kW	0.945	0.945	0.944	0.944	0.942	0.941	0.941	0.941
400 kW	0.945	0.945	0.944	0.944	0.942	0.941	0.941	0.941
450 kW	0.945	0.945	0.944	0.944	0.942	0.941	0.941	0.941
500 kW	0.945	0.945	0.944	0.944	0.942	0.941	0.941	0.941

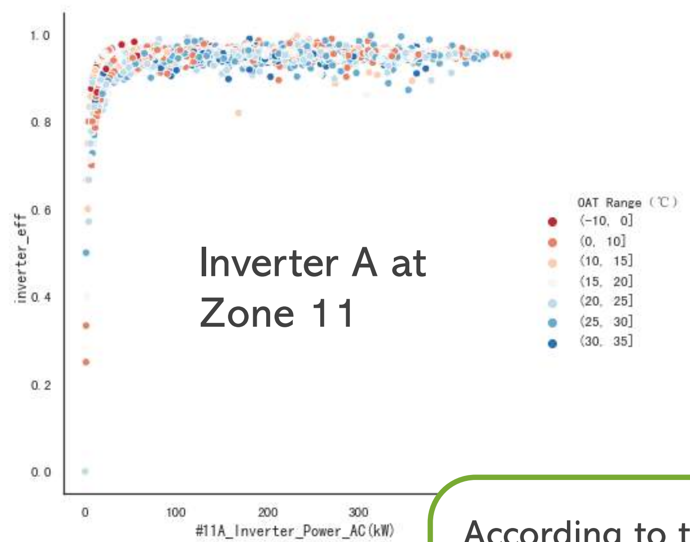


Comparison of Inverter Efficiency

Data from 03/25 to 12/17



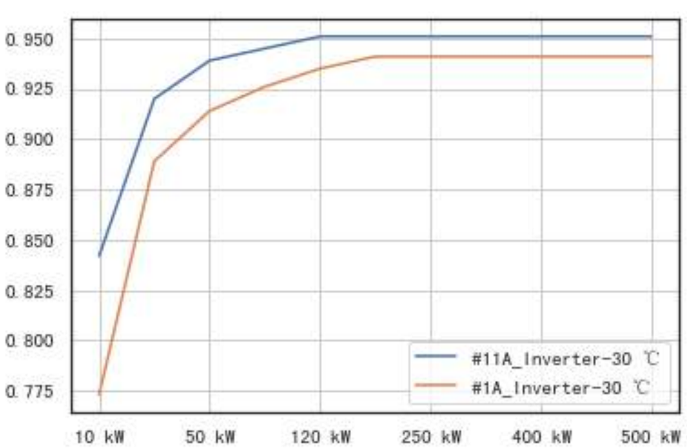
VS



Decision-making support:

- ❑ Equipment health and conditioned maintenance during daily O&M.
- ❑ Reliable intelligence for equipment selection and evaluation during EPC.

According to the performance model
When ambient temperature is 30℃
Efficiency of inverter A at Zone 11 > that of inverter A at Zone 1



	#11A_Inverter-30 ℃	#1A_Inverter-30 ℃
10 kW	0.842	0.773
30 kW	0.920	0.889
50 kW	0.939	0.914
80 kW	0.945	0.926
120 kW	0.951	0.935
180 kW	0.951	0.941
250 kW	0.951	0.941
350 kW	0.951	0.941
400 kW	0.951	0.941
450 kW	0.951	0.941
500 kW	0.951	0.941

	Percent (%)
10 kW	8.93
30 kW	3.49
50 kW	2.74
80 kW	2.05
120 kW	1.71
180 kW	1.06
250 kW	1.06
350 kW	1.06
400 kW	1.06
450 kW	1.06
500 kW	1.06

CONTENTS

Financial Benefit

$500,000/year for a 100MW Plant[1]

40%

- Reduction in power loss

30%

- Increase in work efficiency

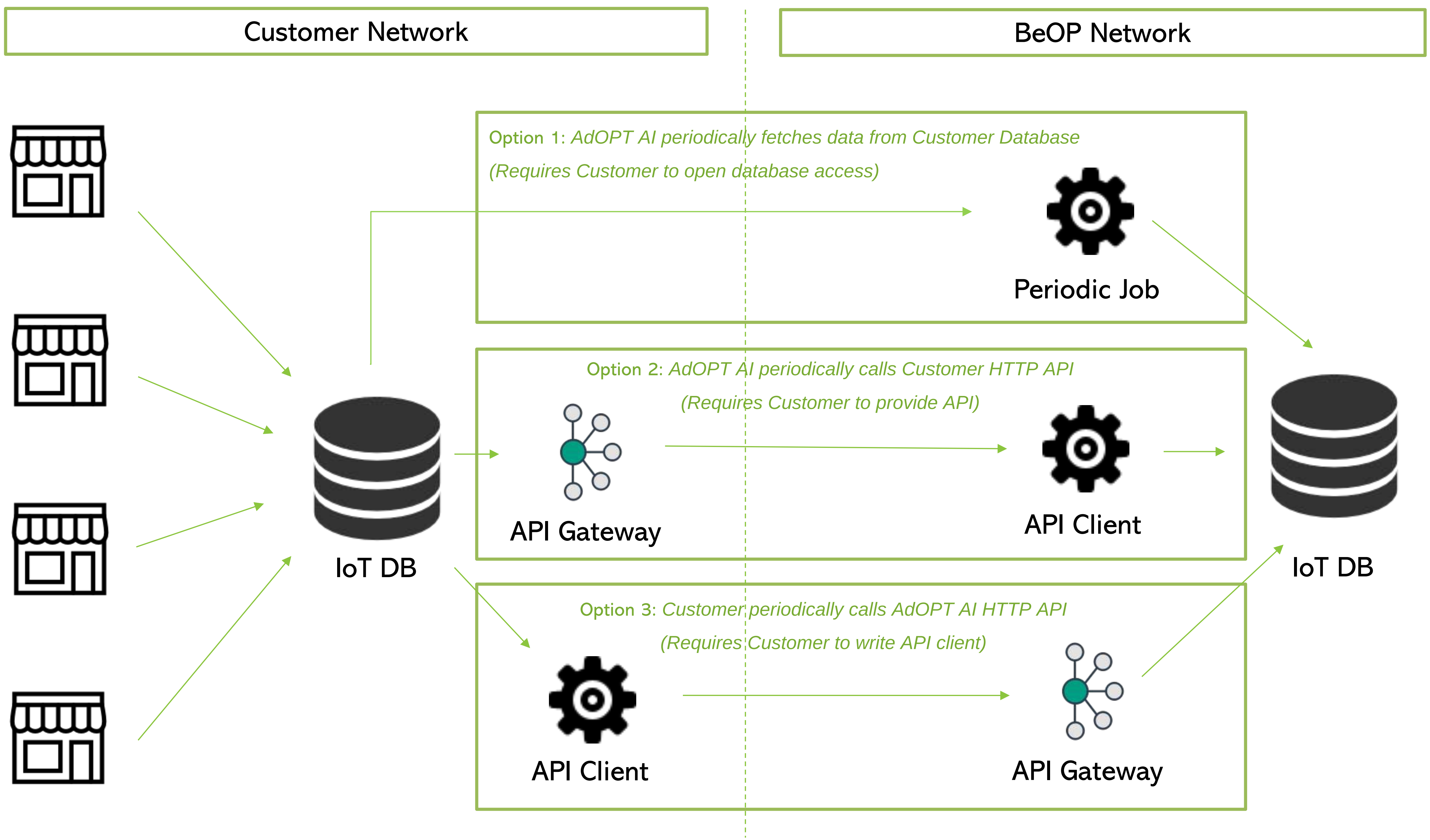
20%

- Decrease in operating & maintenance cost

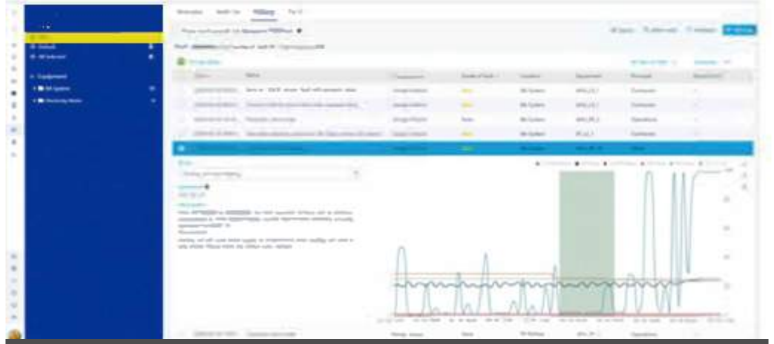
1: https://www.ge.com/renewableenergy/digital-solutions/digital-solar-plant

The End

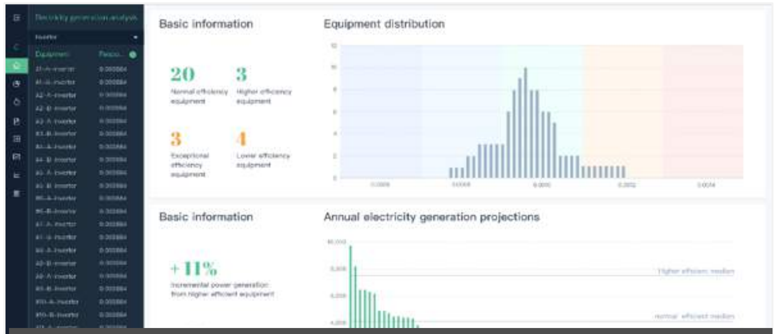
Appendix: Typical Data Integration Architecture



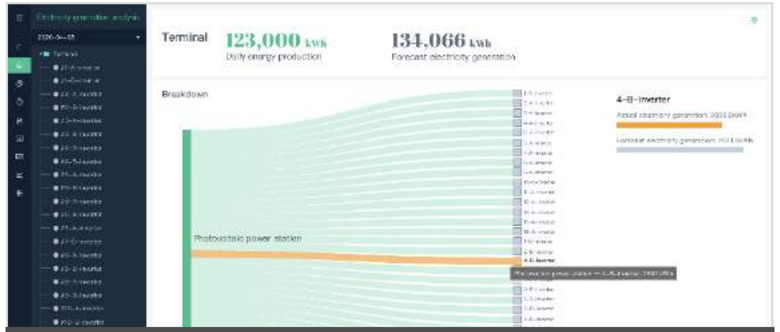
Appendix: Sample User Interface



Automated FDD

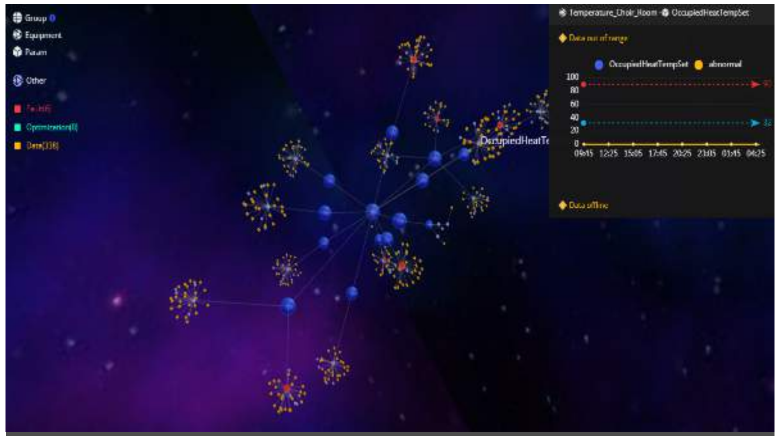


Equipment Performance Analysis

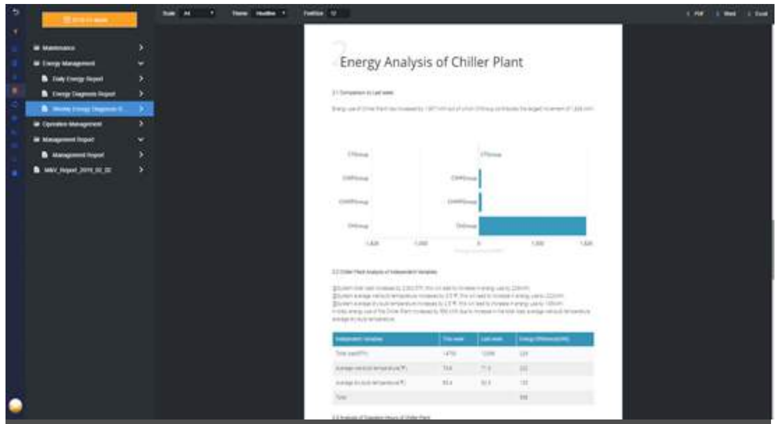


Generation Performance Analysis

Multi-site Analysis



AI Visualization



Automatic Reporting