JTUS, Vol. 3, No. 9 September 2024
E-ISSN: 2984-7435, P-ISSN: 2984-7427
DOI: https://doi.org/

Journal Transnational Universal Studies

Utilization of Advanced Metering Infrastructure (AMI) Data for Optimization of Load Management and Dynamic Pricing at PLN

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Abstract
Advanced Metering Infrastructure (AMI) is a technological system comprising smart meters, communication networks, and data management systems that enable real-time energy consumption data collection. This data is used to analyze usage patterns, identify peak load periods, determine dynamic tariffs, and optimize energy distribution. The system also forms the basis for applying machine learning models to predict future energy consumption and optimize electricity tariff pricing. This research aims to examine how AMI can improve energy consumption data accuracy, support dynamic tariff implementation, and reduce operational costs using machine learning algorithms such as Random Forest and XGBoost. The study also explores the challenges of AMI deployment and strategies to enhance customer participation. By utilizing real-time data and machine learning predictions, AMI allows for timely tariff adjustments, encourages efficient energy consumption, and reduces peak load. The results show that AMI, combined with machine learning and dynamic tariffs, can yield cost savings for both utility companies and consumers, while contributing to environmental sustainability by reducing carbon emissions. Despite challenges, collaboration between governments, utilities, and consumers can ensure the system’s success and sustainability. This study provides valuable insights into the benefits and challenges of AMI and offers recommendations for future development, making AMI a key component in building a more efficient and sustainable energy system.

Keywords: Advanced Metering Infrastructure, dynamic pricing, load management, energy efficiency, smart meters, environmental sustainability

INTRODUCTION

Electricity supply is a very important primary need in human life and is a crucial element in national economic development. In Indonesia, the electricity system covers a vast area from Sumatra to Papua, each of which has its own unique characteristics and challenges. One of the biggest challenges faced is the fluctuation in load patterns, which often show peak loads at almost the same time in many regions. This phenomenon causes significant peak loads, which in Bali's electricity system are recorded at 28,291 MW, putting great pressure on the operational costs of the power plants used to meet these needs (Ahmad et al., 2018; Li et al., 2018; Siano, 2014; Zhang et al., 2021). In addition, Indonesia's electricity system faces a peak load of up to 35 GW, which increases the need for additional plants, often fossil fuel peaker power plants that are more expensive to operate (Silalahi et al., 2023). These high load peaks cause coal- and diesel-fired plants to be used, which increases the cost of electricity for consumers. This, of course, reduces the operational efficiency of energy providers and increases the cost of energy supply for consumers. Therefore, peak load management is very important to ensure smooth energy supply at a cost-efficient rate and to maintain the stability of the national electricity system (Ahmad et al., 2018; Li et al., 2018; Siano, 2014; Zhang et al., 2021).

Currently, Indonesia still relies on flat tariffs, which means that electricity tariffs remain constant all the time without considering differences in production costs that occur at certain times. Power generation costs vary, with higher costs at certain hours, especially during peak loads. This condition causes the tariffs applied to consumers not to reflect the real costs that occur on the producer's side. To address this problem of non-conformity, the implementation of dynamic tariffs based on consumption patterns can be a solution. Dynamic rates allow consumers to pay according to actual generation costs, which are higher during peak hours and lower during non-peak hours, and can motivate changes in consumption patterns to reduce peak loads. The change in tariffs from flat tariffs to dynamic tariffs has the potential to change consumer behavior to optimize loads, which in turn can reduce electricity bills and overall electricity supply costs. On the producer side, the implementation of these dynamic tariffs can reduce reliance on expensive power plants, which have been necessary to cope with peak loads. However, if there is no significant change in consumption patterns, producers will still be compensated through higher tariffs to cover operational costs (Makwarela et al., 2022; Moreno et al., 2014; Valencia-Salazar et al., 2021).

As energy needs increase, efficient and sustainable energy management has become very important. One solution to achieve this is the implementation of Advanced Metering Infrastructure (AMI), which collects real-time energy consumption data. AMI, which consists of smart meters and communication systems, allows utility companies to more accurately monitor electrical loads, identify peak load periods, and shift energy consumption to non-peak periods (Khan & Jayaweera, 2020; Paudyal et al., 2015). The application of dynamic tariffs adapted to market conditions and demand allows for better peak load management (Antonopoulos et al., 2020; Jain & Gupta, 2024; Kaur et al., 2022; Kumar et al., 2022; Ustun et al., 2024; Zhang et al., 2022). By using AMI, utilities can set more precise dynamic rates, as well as leverage machine learning algorithms to analyze historical data and predict future peak loads (Biswas et al., 2025). In addition, machine learning is also used to estimate customer response to dynamic tariffs applied, as well as to optimize the allocation of energy resources, which helps reduce operational costs and avoid costly plant operations.

AMI also supports energy sustainability by encouraging more efficient consumption and reducing carbon emissions (Albogamy et al., 2022). With the ability to monitor energy consumption in real-time, AMI allows for more precise load management and fluctuation management from renewable energy sources such as solar and wind, which have variable properties and are not always stable (Borenstein & Holland, 2022; Carroll et al., 2014; Yang et al., 2013). The implementation of data-driven dynamic tariffs obtained from AMI provides an opportunity to reduce peak loads by encouraging consumers to shift their energy consumption to non-peak periods ((Valencia-Salazar et al., 2021; Zhang et al., 2022). By using predictive results from machine learning, utilities can obtain a more accurate picture of consumer behavior, which in turn can optimize energy management in a more efficient way (Amuthan et al., 2025). Although the implementation of AMI requires a considerable initial investment, the long-term benefits are significant, both in peak load management and in improving the efficiency of renewable energy use (Biswas et al., 2025). With the application of this model, it is hoped that the results of the research can be applied in all regions to reduce dependence on expensive power plants, reduce carbon emissions, and improve the efficiency and sustainability of the electricity system.

Based on the background presented, this study raises several problems related to the application of Advanced Metering Infrastructure (AMI) in energy management. First, this study aims to explore how machine learning models trained with AMI data can be used to project energy consumption and generate daily load curves, which are important for analyzing load fluctuations and predicting future electricity demand. In addition, this study also wants to investigate the application of AMI in supporting the development of dynamic tariff scenarios, such as Time-of-Use (ToU) and Critical Peak Pricing (CPP), as well as their impact on electricity load management. Furthermore, this study will examine how AMI's data-driven dynamic rates can optimize load management, with a focus on reducing peak loads and shifting energy consumption to Off-Peak periods. The study will also evaluate the impact of implementing dynamic tariffs on power plant operating costs and customer monthly costs, as well as how shifting loads can contribute to more efficient energy management. There are several limitations to consider, including data limitations which only include energy consumption from smart meters over a certain period, which can affect the results of the analysis if the data are incomplete. In addition, this study also has a time constraint that affects the duration of data collection and analysis, so the results obtained cannot be generalized for a longer period. Finally, the study assumes that all components of AMI technology function optimally, in the absence of technical interference, although technological limitations and operational constraints will only be discussed theoretically and not empirically tested.

METHODS

The methodology of this study focuses on designing dynamic tariffs for load management based on AMI (Advanced Metering Infrastructure) data. This research process is carried out in several stages as described in Figure 1 below.

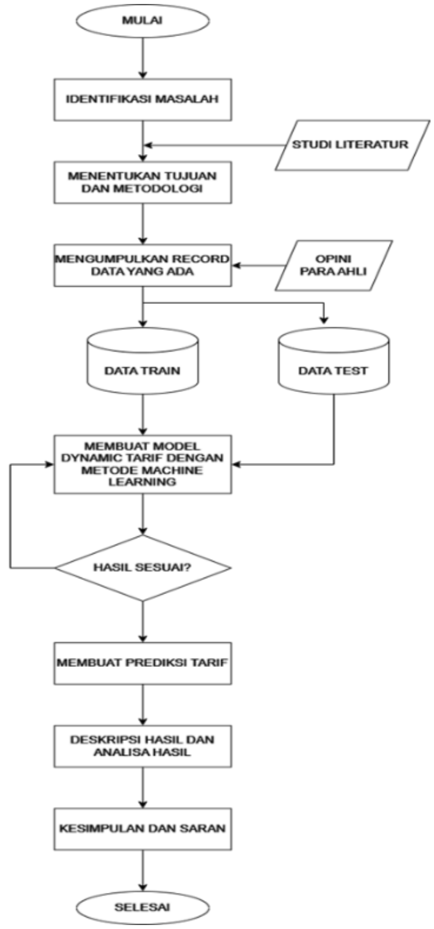

Figure 1 Research flow chart

In this study, the data collection method prioritizes a quantitative approach, which utilizes data taken from the Advanced Metering Infrastructure (AMI). This data collection is done without involving interviews or qualitative data collection through direct interaction with customers. Instead, energy consumption data collected through AMI is used to predict future energy consumption patterns, as well as develop an efficient dynamic tariff system.

RESULTS AND DISCUSSION

Projected Electrical Energy Produced

Electricity load forecasting is carried out for the analysis of the cost of generation (BPP) based on the use of the power plant listed every hour. The data used in this study refers to the projected power plant usage calculated using LEAP software with Business As Usual (BAU) mode.

Table 1 shows the use of different types of power plants used on an hourly basis over a period of time. The types of plants used include vagrious technologies, such as coal-based plants (subcritical, supercritical, and ultra supercritical), gas turbine combine cycle, biomass, hydro, and photovoltaic (PV). Each type of plant has a varied capacity, which is adapted to the energy needs at certain hours.

Table 1. Cost of Generation per Generation per Generation per Hour

Branch	Coal Subcritical	Coal Supercritical	Coal Ultra Supercritical	Gas Turbine Combine Cycle	Biomass	Hydropower	Medium Hydro	Mini Micro Hydro	Utility Scale PV	Industrial PV	Floating PV	Geothermal Flash or Dry	Total
	786,88	**786,88**	**786,88**	**1473,18**	**786,88**	**464,5**	**464,5**	**464,5**	**11619,66**	**11619,66**	**11619,66**	**1220,68**	
Hr 1	123,96	427,10	139,00	-	0,27	42,20	2,26	0,32	-	-	-	32,07	**767,19**
Hr 2	115,78	432,38	140,72	-	0,27	42,73	2,29	0,33	-	-	-	32,47	**766,95**
Hr 3	98,79	443,32	144,28	-	0,28	43,81	2,35	0,33	-	-	-	33,29	**766,45**
Hr 4	107,39	437,78	142,48	-	0,28	43,26	2,32	0,33	-	-	-	32,87	**766,70**
Hr 5	131,94	421,96	137,33	-	0,27	41,70	2,23	0,32	0,03	0,04	0,11	31,69	**767,60**
Hr 6	139,09	416,93	135,69	-	0,26	41,20	2,21	0,31	-	-	-	31,31	**767,00**
Hr 7	130,36	421,96	137,33	-	0,27	41,70	2,23	0,32	-	-	-	31,69	**765,84**
Hr 8	174,00	393,51	128,07	-	0,25	38,88	2,08	0,30	-	-	-	29,55	**766,64**
Hr 9	164,74	372,58	121,26	77,69	0,24	36,82	1,97	0,28	-	-	-	27,98	**803,55**
Hr 10	161,31	364,82	118,73	106,42	0,23	36,05	1,93	0,27	-	-	-	27,39	**817,16**
Hr 11	159,65	361,06	117,51	120,39	0,23	35,68	1,91	0,27	-	-	-	27,11	**823,80**
Hr 12	163,01	368,66	119,98	92,01	0,23	36,43	1,95	0,28	-	-	-	27,68	**810,23**
Hr 13	159,65	361,06	117,51	120,86	0,23	35,68	1,91	0,27	-	-	-	27,11	**824,27**
Hr 14	154,86	350,22	113,98	162,05	0,22	34,61	1,85	0,26	-	-	-	26,30	**844,36**
Hr 15	156,42	353,76	115,13	149,78	0,22	34,96	1,87	0,27	-	-	-	26,56	**838,98**
Hr 16	158,02	357,37	116,31	137,62	0,23	35,31	1,89	0,27	-	-	-	26,84	**833,86**
Hr 17	161,31	364,82	118,73	110,96	0,23	36,05	1,93	0,27	-	-	-	27,39	**821,70**
Hr 18	154,86	350,22	113,98	165,55	0,22	34,61	1,85	0,26	-	-	-	26,30	**847,86**
Hr 19	159,65	361,06	117,51	125,11	0,23	35,68	1,91	0,27	-	-	-	27,11	**828,52**
Hr 20	163,01	368,66	119,98	96,73	0,23	36,43	1,95	0,28	-	-	-	27,68	**814,95**
Hr 21	166,52	376,59	122,56	67,13	0,24	37,21	1,99	0,28	-	-	-	28,28	**800,80**
Hr 22	172,07	389,14	126,64	20,26	0,25	38,45	2,06	0,29	-	-	-	29,22	**778,38**
Hr 23	154,80	407,24	132,54	-	0,26	40,24	2,15	0,31	-	-	-	30,58	**768,11**
Hr 24	123,96	427,10	139,00	-	0,27	42,20	2,26	0,32	-	-	-	32,07	**767,19**
Total	**146.154,27**	**377.810,65**	**122.957,99**	**67.774,14**	**239,31**	**37.333,54**	**1.998,84**	**284,27**	**1.942,21**	**2.957,62**	**7.932,95**	**28.370,56**	**795.756,34**

The use of hourly power plant data in this study makes it possible to calculate the BPP used per hour. BPP is the cost incurred to generate electricity at a particular plant. Thus, BPP will differ based on the type of generator and the number of generators used at each hour. Through this BPP calculation, we can further understand how changes in energy use

Flat Rate

Flat tariff is a type of block tariff set by PT. PLN (Persero), where customers are grouped based on the power capacity they request. Each of these customer groups is subject to a fixed rate that does not change, regardless of usage time. The main feature of these tariffs is that the price is determined based on the customer class, not the time of energy use.

The advantage of flat rates is price stability, which makes it easier for customers to estimate monthly electricity costs. In contrast to dynamic rates, these rates do not consider usage time, making them more suitable for customers with stable consumption patterns. This rate is perfect for customers who do not change their electricity usage habits frequently, both during the day and at night.

However, flat tariffs also have disadvantages because they cannot regulate energy consumption at certain times, such as when peak loads occur. This tariff system tends to use generation capacity continuously without taking into account peak load periods, so it is less flexible in reducing load at certain hours.

Table 2. Basic Electricity Tariff April – June 2025

No.	Tariff Cat.	Power Limits	Load Fee (Rp/kVA/month)	Usage Fee (Rp/kWh) and kVA Fee (Rp/kVAh)	Prepaid (Rp/kWh)
1	R-1/TR	900 VA-RTM	*)	1.352,00	1.444,70
2	R-1/TR	1.300 VA	*)	1.444,70	1.444,70
3	R-1/TR	2.200 VA	*)	1.444,70	1.444,70
4	R-2/TR	s.d. 5.500 VA	*)	1.699,53	1.699,53
5	R-3/TR, TM	6.600 VA	*)	1.699,53	1.699,53
6	B-2/TR	s.d. 200 kVA	*)	1.444,70	1.444,70
7	B-3/TM, TT	above 200 kVA	*)	WBP Block = K x 1,035.78Block LWBP = 1,035.78kVArh = 1,114.74 ****)	-
8	I-3/TM	above 200 kVA	*)	WBP Block = K x 1,035.78Block LWBP = 1,035.78kVArh = 1,114.74 ****)	-
9	I-4/TM	30,000 kVA and above	*)	WBP Block = K x 1,035.78Block LWBP = 1,035.78kVArh = 1,114.74 ****)	-
10	P-1/TR	6,600 kVA	*)	1.699,53	1.699,53
11	P-2/TM	above 200 kVA	*)	WBP Block = K x 1,035.78Block LWBP = 1,035.78kVArh = 1,114.74 ****)	-
12	P-3/TR	above 200 kVA	*)	1.699,53	1.699,53
13	L/TTR, TM, TT	-	*)	WBP Block = K x 1,035.78Block LWBP = 1,035.78kVArh = 1,114.74 ****)	-

Dynamic Tariff Proposal

Dynamic electricity tariffs are a type of tariff that changes according to time, where the amount of tariffs will depend on the pattern of electrical energy use at certain hours. The implementation of dynamic tariffs aims to manage energy use more efficiently, encourage consumers to adjust their energy consumption patterns, and reduce the burden on the electricity supply system. In addition, this tariff also focuses on the gradual reduction of energy subsidies and ensures a fairer distribution of costs.

The implementation of dynamic tariffs will be more effective if it is supported by Advanced Metering Infrastructure (AMI), which allows for more accurate measurement and monitoring of energy consumption in each customer. With a good understanding of this dynamic tariff system, customers are expected to be more involved in managing their energy consumption.

Proposed ToU Tariff with Machine Learning

Based on the data obtained from the AMI system, it can be seen that the pattern of electricity consumption shows significant fluctuations throughout the day. The peak of consumption generally occurs at certain hours, such as between 16:00 and 22:00. This pattern provides a solid foundation for designing more efficient dynamic rates, leveraging Time-of-Use (ToU). The implementation of ToU pricing allows the determination of different tariffs according to the time of energy consumption.

The implementation of ToU tariffs aims to stimulate energy savings and improve the efficiency of the power grid. Therefore, the time of energy use is divided into several time segments, namely Off Peak, Mid Day, and On Peak. Each of these segments has a tariff adjusted to the pattern of electricity use at those hours.

To obtain this time segmentation, we used a pre-trained Machine Learning model, namely using Random Forest and XGBoost. In the previous sub-chapter, it has been explained how the models are trained to predict electrical loads and generate time clusters based on those predictions. The results of this prediction are used to group time into Off Peak, Mid Day, and On Peak segments, according to the consumption patterns generated by the model.

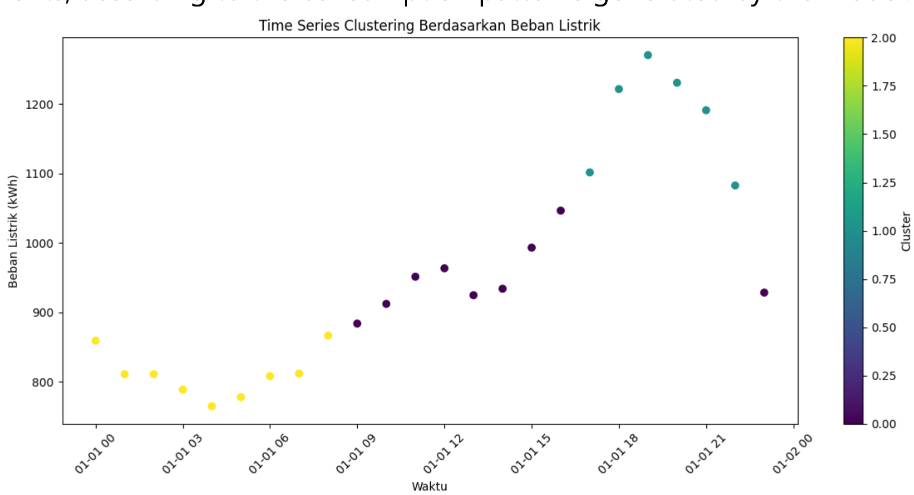

Figure 2. Clustering ToU by Electrical Load

Based on Machine Learning calculations using Random Forest and XGBoost, the time segments for ToU deployment have been defined as follows:

a. Off Peak (23:00 - 08:00): In this time segment, electricity consumption tends to be low, so the tariff charged is also cheaper. Based on the table, the ToU tariff for Off Peak is IDR 1,190.69 per kWh, with a usage duration of 9 hours. The formula for calculating this tariff is BPP + Electricity Provider Margin + Transmission and Distribution Costs.
b. Mid Day (08:00 - 16:00): At this time, electricity consumption is starting to increase, but not as high as in the On Peak segment. The tariff charged on Mid Day is IDR 1,699.53 per kWh, with a duration of 8 hours. These rates are based on the current base rate.
c. On Peak (16:00 - 23:00): This On Peak time segment recorded the highest electricity consumption. To adjust to the high consumption pattern at that time, the tariff charged is also higher, namely IDR 2,935.28 per kWh, with a usage duration of 7 hours. The formula used is 24-hour base rate - 17 hours + Peak off rate x 7 hours.

With this time segmentation, it is hoped that there will be a partial transfer of energy consumption to cheaper Off Peak times, so as to reduce the load on the power grid during more congested and expensive On Peak times. Table 3 presents the time segmentation for the implementation of Time-of-Use (ToU) based on daily electricity consumption patterns obtained from AMI data

Table 3. ToU Tariff Scheme

Segment	Time	t (jam)	ToU (Rp/kWh)	Formula
Off Peak	23:00 - 08:00	9	1.190,69	BPP + Electricity Provider Margin + Transmission and Distribution Costs
Mid Day	08:00 - 16:00	8	1.699,53	Current flat rates
On Peak	16:00 - 23:00	7	2.935,28	(Base fare x 24 hours - 17 hours x Off Peak fare)/7 Hours

Proposed CPP Tariff

Based on the table provided, the proposed Critical Peak Pricing (CPP) tariff is designed to encourage a reduction in electricity consumption at very critical hours with higher rates at certain times and lower rates at other times. Here is a detailed explanation of the table that includes the time segments and proposed rates:

a. Off Peak (23:00 - 17:00): In this time segment, electricity consumption is generally low, so the tariff charged is IDR 1,190.69 per kWh. The duration of time is 18 hours, and the tariff is calculated based on the average LCOE + Electricity Provider Margin + Transmission and Distribution Costs.
b. Critical Peak (17:00 - 19:00): In this time segment, the tariff charged is higher, which is Rp 3,572.07 per kWh, with a duration of 2 hours. This rate is imposed because electricity consumption is at its peak at this time, so the rate is higher to encourage consumption reduction during those hours. The formula used to calculate the rates in this segment is: (Basic fare×24 hours−18 hours×Off Peak fare)/2 Hours
c. On Peak (19:00 - 23:00): In the On Peak segment, the tariff charged is IDR 2,829.15 per kWh, with a duration of 4 hours. The formula used to calculate the rates in this segment is: (Basic rate×24 hours−18 hours×Off Peak rate)/4 Hours

Through this Critical Peak Pricing (CPP) scheme, it is hoped that consumers can shift part of their consumption at cheaper Off Peak times, so that it can reduce the burden on the electricity system during On Peak which requires greater energy supply and higher costs.

Table 4. CPP Tariff Scheme

Segmen	Time	t (jam)	CPP (Rp/kWh)	Formula
Off-Peak	23:00 - 17:00	18	1.190,69	Average LCOE + Electricity Provider Margin + Transmission and Distribution Costs
Critical	17:00 - 19:00	2	3.572,07	(Peak off Fare x 24 hours - 18 hours x Off Peak Fare)/2 Hours
On-Peak	19:00 - 23:00	4	2.829,15	(Base rate x 24 hours - 18 hours x Off Peak rate)/4 Hours

Comparison of ToU Tariff Electricity Cost with Flat Tariff

The comparison of the cost of electricity consumption between the implementation of the Flat Tariff and the Time-of-Use (ToU) tariff based on the daily load profile (in kWh) is shown in the existing table. This data is part of the cost comparison analysis before load shifting. This table specifically describes the fluctuations in electricity costs throughout the day, both at standard rates (Flat) and rates adjusted for the time of use (ToU).

From the table, it can be seen that at some hours, such as between 23:00 to 08:00, the ToU Tariff shows a lower cost than the Flat Tariff, providing a savings opportunity for customers. In contrast, during peak hours, such as between 16:00 and 23:00, ToU Tariffs actually result in higher costs, reflecting an incentive to move electricity consumption outside of peak periods. This data is an important basis for analyzing the effectiveness of using dynamic tariffs for electricity load management and cost optimization for users.

Table 5. Comparison of ToU Tariff Electricity Cost with Flat Tariff

Time	Load (KWh)	Energy Usage Cost (Rp)	
		Flat Tariff (Rp)	Time of Use (Rp)
00:00	889	1.511.275	1.058.799
01:00	854	1.451.269	1.016.759
02:00	825	1.402.491	982.585
03:00	807	1.371.833	961.106
04:00	797	1.354.800	949.172
05:00	818	1.389.845	973.725
06:00	875	1.486.572	1.041.492
07:00	935	1.588.876	1.113.166
08:00	1.015	1.725.345	1.725.345
09:00	1.068	1.815.780	1.815.780
10:00	1.078	1.832.678	1.832.678
11:00	1.089	1.850.821	1.850.821
12:00	1.105	1.878.132	1.878.132
13:00	1.077	1.830.152	1.830.152
14:00	1.070	1.818.496	1.818.496
15:00	1.150	1.953.774	1.953.774
16:00	1.225	2.081.839	3.595.575
17:00	1.382	2.349.201	4.057.338
18:00	1.419	2.411.792	4.165.440

Time	Load (KWh)	Energy Usage Cost (Rp)	
		Flat Tariff (Rp)	Time of Use (Rp)
19:00	1.418	2.410.051	4.162.434
20:00	1.371	2.329.476	4.023.272
21:00	1.317	2.237.735	3.864.824
22:00	1.183	2.010.948	3.473.137
23:00	997	1.694.149	1.186.921
Total	25.764	43.787.330	51.330.925
Total/Month		**1.313.619.887**	**1.539.927.763**

The table above shows that the implementation of Time-of-Use (ToU) Tariffs without changes in electricity consumption patterns from customers tends to result in higher monthly electricity costs compared to the use of Flat Tariffs. The total cost of monthly energy consumption with ToU rates reaches around IDR 1.54 billion, higher than the flat rate which is currently only IDR 1.31 billion. This confirms that the implementation of dynamic tariffs requires adjusting consumption to obtain optimal cost efficiency benefits.

Comparison of ToU Tariff Electricity Cost with Flat Tariff After Load Shifting

After conducting a comparative analysis of electricity costs between Flat Tariff and Time-of-Use (ToU) Tariff under initial load conditions (without shifting), the next step is to evaluate the impact of implementing the load shifting strategy. This table, entitled "Comparison of ToU Tariff Electricity Cost with Flat Tariff After Load Shifting", presents an overview of the potential savings that can be obtained if some electricity consumption is shifted from peak to non-peak hours.

The table shows that the greater the percentage of load shifting ranging from 0% to 100%, the total monthly electricity cost with the ToU Tariff tends to decrease the further. In the scenario without shifting (0%), the monthly cost with the ToU rate was recorded at IDR 1,477,999,746, higher than the flat rate of IDR 1,313,619,887. However, as the percentage of shifting increases, there are progressive savings. For example, at a 50% shift, the monthly savings reach IDR 100,845,533, and at a maximum shift of 100%, the savings increase to IDR 305,161,804 per month or around IDR 3.66 billion per year.

Table 6. Comparison of ToU Tariff Electricity Cost with Flat Tariff After Load Shifting

Shifting (%)	Total Flat Fee/Month (Rp)	Total ToU Fee/Month (Rp)	Monthly savings ToU vs Flat Tariff (Rp)	Annual savings of ToU vs Flat Tariff (Rp)
0	1.313.619.887	1.477.999.746	-164.379.860	-1.972.558.315
5	1.313.619.887	1.396.658.997	-83.039.110	-996.469.323
10	1.313.619.887	1.376.227.370	-62.607.483	-751.289.798
15	1.313.619.887	1.355.795.743	-42.175.856	-506.110.273
20	1.313.619.887	1.335.364.116	-21.744.229	-260.930.748
25	1.313.619.887	1.314.932.489	-1.312.602	-15.751.223
30	1.313.619.887	1.294.500.862	19.119.025	229.428.302
35	1.313.619.887	1.274.069.235	39.550.652	474.607.827
40	1.313.619.887	1.253.637.607	59.982.279	719.787.352
45	1.313.619.887	1.233.205.980	80.413.906	964.966.877
50	1.313.619.887	1.212.774.353	100.845.533	1.210.146.402
55	1.313.619.887	1.192.342.726	121.277.161	1.455.325.926
60	1.313.619.887	1.171.911.099	141.708.788	1.700.505.451

Shifting (%)	Total Flat Fee/Month (Rp)	Total ToU Fee/Month (Rp)	Monthly savings ToU vs Flat Tariff (Rp)	Annual savings of ToU vs Flat Tariff (Rp)
65	1.313.619.887	1.151.479.472	162.140.415	1.945.684.976
70	1.313.619.887	1.131.047.845	182.572.042	2.190.864.501
75	1.313.619.887	1.110.616.218	203.003.669	2.436.044.026
80	1.313.619.887	1.090.184.591	223.435.296	2.681.223.551
85	1.313.619.887	1.069.752.964	243.866.923	2.926.403.076
90	1.313.619.887	1.049.321.337	264.298.550	3.171.582.601
95	1.313.619.887	1.028.889.710	284.730.177	3.416.762.126
100	1.313.619.887	1.008.458.083	305.161.804	3.661.941.651

Table 6 presents a comparison of electricity costs between Time-of-Use (ToU) and Flat Tariff after load shifting efforts, i.e. shifting part of energy consumption from On Peak hours (peak time) to Off Peak hours (low load time). The goal of this strategy is to reduce the total electricity cost of customers and improve the efficiency of energy consumption, both monthly and annually.

a. In the 0% shifting condition, consumption patterns have not changed. As a result, electricity costs with ToU tariffs are higher than Flat tariffs, resulting in a savings deficit of IDR -164,379,860 per month or around IDR -1,972,558,315 per year.
b. When the shifting increases to 100%, the entire energy consumption is moved to the Off Peak clock. In this condition, the ToU tariff actually provides a significant cost advantage compared to the Flat tariff. The monthly savings reached IDR 305,161,804, and on an annual basis increased to IDR 3,661,941,651.

This table shows that with the implementation of optimal load shifting, customers can achieve significant electricity cost savings, both monthly and yearly. Moving energy consumption to periods with lower rates, such as during Off Peak hours, will result in greater savings, especially when the percentage shifting of loads is getting higher.

Table 7. Electricity Cost Savings ToU Tariff with Flat Tariff After Load Shifting

Shifting (%)	Total ToU Fee/Month (Rp)	Savings Per Year ToU Shifting vs No Shifting (Rp)	Monthly Savings ToU Shifting vs No Shifting (Rp)	Monthly Savings ToU Shifting vs No Shifting (%)
0	1.477.999.746	-1.972.558.315	-164.379.860	-11,12%
5	1.396.658.997	-996.469.323	-83.039.110	-5,62%
10	1.376.227.370	-751.289.798	-62.607.483	-4,24%
15	1.355.795.743	-506.110.273	-42.175.856	-2,85%
20	1.335.364.116	-260.930.748	-21.744.229	-1,47%
25	1.314.932.489	-15.751.223	-1.312.602	-0,09%
30	1.294.500.862	229.428.302	19.119.025	1,29%
35	1.274.069.235	474.607.827	39.550.652	2,68%
40	1.253.637.607	719.787.352	59.982.279	4,06%
45	1.233.205.980	964.966.877	80.413.906	5,44%
50	1.212.774.353	1.210.146.402	100.845.533	6,82%
55	1.192.342.726	1.455.325.926	121.277.161	8,21%
60	1.171.911.099	1.700.505.451	141.708.788	9,59%
65	1.151.479.472	1.945.684.976	162.140.415	10,97%

Shifting (%)	Total ToU Fee/Month (Rp)	Savings Per Year ToU Shifting vs No Shifting (Rp)	Monthly Savings ToU Shifting vs No Shifting (Rp)	Monthly Savings ToU Shifting vs No Shifting (%)
70	1.131.047.845	2.190.864.501	182.572.042	12,35%
75	1.110.616.218	2.436.044.026	203.003.669	13,74%
80	1.090.184.591	2.681.223.551	223.435.296	15,12%
85	1.069.752.964	2.926.403.076	243.866.923	16,50%
90	1.049.321.337	3.171.582.601	264.298.550	17,88%
95	1.028.889.710	3.416.762.126	284.730.177	19,26%
100	1.008.458.083	3.661.941.651	305.161.804	20,65%

Comparison of CPP Tariff Electricity Cost with Flat Tariff

A comparative analysis of the cost of electricity consumption between the standard tariff (Flat Tariff) and the Critical Peak Pricing (CPP) tariff based on the daily load profile (in kWh) shows a significant difference in cost between the two tariff schemes. This table illustrates how electricity costs vary throughout the day under the two tariff schemes. At most hours, especially outside of peak periods, the cost at the CPP rate tends to be lower or equivalent to the Flat rate. However, in hours that are considered critical peak periods (such as 17:00 to 19:00), CPP rates show a very high cost spike, much larger compared to Flat rates. This aims to incentivize consumers to drastically reduce electricity use during this period to ease the burden on the electricity system. The "Total" and "Total/Month" columns at the bottom of the table show the total daily and monthly energy costs for both tariff schemes, allowing for a direct evaluation of the effectiveness of CPP tariffs in reducing costs and managing energy demand.

Table 8. Comparison of Flat Tariff Electricity Cost with CPP Tariff

Time	Load (KWh)	Energy Usage Cost (Rp)	
		Flat Tariff (Rp)	CPP (Rp)
00:00	889	1.511.275	1.058.799
01:00	854	1.451.269	1.016.759
02:00	825	1.402.491	982.585
03:00	807	1.371.833	961.106
04:00	797	1.354.800	949.172
05:00	818	1.389.845	973.725
06:00	875	1.486.572	1.041.492
07:00	935	1.588.876	1.113.166
08:00	1.015	1.725.345	1.208.777
09:00	1.068	1.815.780	1.272.135
10:00	1.078	1.832.678	1.283.974
11:00	1.089	1.850.821	1.296.685
12:00	1.105	1.878.132	1.315.819
13:00	1.077	1.830.152	1.282.205
14:00	1.070	1.818.496	1.274.038
15:00	1.150	1.953.774	1.368.814
16:00	1.225	2.081.839	1.458.536

Time	Load (KWh)	Energy Usage Cost (Rp)	
		Flat Tariff (Rp)	CPP (Rp)
17:00	1.382	2.349.201	4.937.549
18:00	1.419	2.411.792	5.069.103
19:00	1.418	2.410.051	4.011.932
20:00	1.371	2.329.476	3.877.802
21:00	1.317	2.237.735	3.725.083
22:00	1.183	2.010.948	3.347.558
23:00	997	1.694.149	1.186.921
Total	25.764	43.787.330	46.013.737
Total/Month		**1.313.619.887**	**1.380.412.119**

At the Flat rate, the monthly electricity cost is calculated at a fixed rate around the clock without considering the hours of energy consumption. This means that even though there is an increase in electricity load during peak hours, the tariff charged is no different from other hours. The total monthly cost with the Flat rate is IDR 1,313,619,887.

Meanwhile, at Critical Peak Pricing (CPP) or Time-of-Use (ToU) tariffs, electricity costs are calculated based on energy usage at certain hours. In hours that are considered peak (On Peak), the rate charged is higher, while in the lower hours of usage (Off Peak), the rate charged is cheaper. Based on the existing table, we can see that the total cost with the CPP (ToU) tariff scheme is higher compared to the Flat tariff. The total monthly cost with the CPP rate is IDR 1,380,412,119, which is higher around IDR 66,792,232 compared to the Flat rate.

This table shows that while CPP rates in some hours provide cost savings, overall CPP rates are more expensive than Flat rates for total monthly usage. However, the CPP tariff scheme still has the potential to manage energy demand more efficiently by shifting some of the consumption to cheaper times, despite the additional costs at certain hours.

Comparison of CPP Tariff Electricity Cost with Flat Tariff After Load Shifting

After evaluating the electricity cost comparison between the Flat tariff and the Critical Peak Pricing (CPP) tariff based on the initial load profile, the next analysis is focused on the impact of the load shifting strategy. The table given shows a simulation of the potential savings that can be achieved by consumers when they actively shift electricity consumption from the critical peak period to the off-peak period.

As the percentage of load shifting increases (from 0% to 100%), the total monthly cost under the CPP tariff scheme decreases, while the resulting savings compared to the Flat rate increases. This data shows how changes in costs are progressively impacting total monthly costs and resulting in significant savings. This analysis is critical to understanding the effectiveness of CPP tariffs as a powerful demand management tool, as well as the potential for reducing operational costs and improving the overall efficiency of the electrical system.

Table 9. Comparison of CPP Tariff Electricity Cost with Flat Tariff After Load Shifting

Shifting (%)	Total CPP Fee/Month (Rp)	Savings Per Year CPP Shifting vs No Shifting (Rp)	Monthly Savings CPP Shifting vs No Shifting (Rp)	Monthly Savings CPP Shifting vs No Shifting (%)
0	1.380.412.119	-801.506.786	-66.792.232	-4,84%
5	1.333.852.186	-242.787.595	-20.232.300	-1,47%
10	1.287.292.254	315.931.595	26.327.633	1,91%
15	1.240.732.321	874.650.785	72.887.565	5,28%
20	1.194.172.389	1.433.369.976	119.447.498	8,65%
25	1.147.612.456	1.992.089.166	166.007.431	12,03%
30	1.101.052.524	2.550.808.356	212.567.363	15,40%
35	1.054.492.591	3.109.527.547	259.127.296	18,77%
40	1.007.932.659	3.668.246.737	305.687.228	22,14%
45	961.372.726	4.226.965.928	352.247.161	25,52%
50	914.812.794	4.785.685.118	398.807.093	28,89%
55	868.252.861	5.344.404.308	445.367.026	32,26%
60	821.692.929	5.903.123.499	491.926.958	35,64%
65	775.132.996	6.461.842.689	538.486.891	39,01%
70	728.573.063	7.020.561.880	585.046.823	42,38%
75	682.013.131	7.579.281.070	631.606.756	45,75%
80	635.453.198	8.138.000.260	678.166.688	49,13%
85	588.893.266	8.696.719.451	724.726.621	52,50%
90	542.333.333	9.255.438.641	771.286.553	55,87%
95	495.773.401	9.814.157.832	817.846.486	59,25%
100	449.213.468	10.372.877.022	864.406.418	62,62%

Next, a more detailed analysis of the savings from the application of Time-of-Use (ToU) tariffs when consumers shift loads. This table specifically shows the Total ToU Cost per Month (Rp) at various load shifting percentages. In addition, this table also measures the Savings Per Year of ToU Shifting vs No Shifting (Rp), Savings Per Month of ToU Shifting vs No Shifting (Rp), and Savings Per Month of ToU Shifting vs No Shifting (%). This data shows quantitatively how the greater the percentage of load shifting carried out by consumers, the more significant the monthly and annual electricity cost savings they can get compared to conditions without load shifting.

Example:

a. At 0% shifting, there are no savings relative to the condition without shifting, with monthly savings of IDR -66,792,232 and annual savings of IDR -801,506,786.
b. At a 10% shift, the savings per month reached IDR 26,327,633 and annual IDR 315,931,595.
c. At a 50% shift, the savings per month reached IDR 398,807,093, with an annual savings of IDR 4,785,685,118.
d. At 100% shifting, the savings per month can reach IDR 864,406,418, with an annual savings of IDR 10,372,877,022.

This demonstrates the effectiveness of ToU tariffs in driving changes in energy consumption behavior that benefit consumers and the electricity system as a whole, with potential savings increasing as load shifts increase.

Table 10. Electricity Cost Savings CPP Tariff with Flat Tariff After Load Shifting

Shifting (%)	Total CPP Fee/Month (Rp)	Savings Per Year CPP Shifting vs No Shifting (Rp)	Monthly Savings CPP Shifting vs No Shifting (Rp)	Monthly Savings CPP Shifting vs No Shifting (%)
0	1.380.412.119	-801.506.786	-66.792.232	-4,84%
5	1.333.852.186	-242.787.595	-20.232.300	-1,47%
10	1.287.292.254	315.931.595	26.327.633	1,91%
15	1.240.732.321	874.650.785	72.887.565	5,28%
20	1.194.172.389	1.433.369.976	119.447.498	8,65%
25	1.147.612.456	1.992.089.166	166.007.431	12,03%
30	1.101.052.524	2.550.808.356	212.567.363	15,40%
35	1.054.492.591	3.109.527.547	259.127.296	18,77%
40	1.007.932.659	3.668.246.737	305.687.228	22,14%
45	961.372.726	4.226.965.928	352.247.161	25,52%
50	914.812.794	4.785.685.118	398.807.093	28,89%
55	868.252.861	5.344.404.308	445.367.026	32,26%
60	821.692.929	5.903.123.499	491.926.958	35,64%
65	775.132.996	6.461.842.689	538.486.891	39,01%
70	728.573.063	7.020.561.880	585.046.823	42,38%
75	682.013.131	7.579.281.070	631.606.756	45,75%
80	635.453.198	8.138.000.260	678.166.688	49,13%
85	588.893.266	8.696.719.451	724.726.621	52,50%
90	542.333.333	9.255.438.641	771.286.553	55,87%
95	495.773.401	9.814.157.832	817.846.486	59,25%
100	449.213.468	10.372.877.022	864.406.418	62,62%

The Impact of ToU Tariffs on the Reduction of Cost of Generation

Next, an analysis is presented on how the implementation of Time-of-Use (ToU) tariffs and load shifting strategies by consumers can have an impact on the operational efficiency of the electricity system, especially in terms of reducing the cost of supply (BPP) of generation. This table shows the BPP ToU per Month (Rp) for conditions without load shifting and after load shifting at various percentages (from 0% to 100%).

Furthermore, this table quantitatively illustrates the Monthly Savings (Rp), Monthly Savings (%), Annual Savings (Rp), and Annual Savings (%) resulting from load shifting. This data indicates that the higher the percentage of load shifting carried out by consumers, the greater the reduction in generation BPP that can be achieved. For example, at 0% shifting, no savings occur. However, when the shift in burden reaches 100%, there is a monthly BPP saving of IDR 10,044,328, which is equivalent to a saving of 3.89% per month or around IDR 120,531,930 per year. This shows that the load shifting driven by ToU tariffs not only benefits consumers, but also has a significant positive impact on operational efficiency and overall costs for electricity supply companies.

Table 11. The Impact of ToU Tariffs on the Reduction of Cost of Generation

Shifting (%)	BPP ToU No Shifting/Month (Rp)	BPP ToU Shifting/Month (Rp)	Savings per month (Rp)	Monthly savings (%)	Savings Per Year (Rp)	Savings Per Year (%)
0	258.496.168	258.496.168	0	0,00%	0	0,00%
5	258.496.168	257.993.951	502.216	0,19%	6.026.597	0,19%
10	258.496.168	257.491.735	1.004.433	0,39%	12.053.193	0,39%
15	258.496.168	256.989.519	1.506.649	0,58%	18.079.790	0,58%
20	258.496.168	256.487.302	2.008.866	0,78%	24.106.386	0,78%
25	258.496.168	255.985.086	2.511.082	0,97%	30.132.983	0,97%
30	258.496.168	255.482.869	3.013.298	1,17%	36.159.579	1,17%
35	258.496.168	254.980.653	3.515.515	1,36%	42.186.176	1,36%
40	258.496.168	254.478.437	4.017.731	1,55%	48.212.772	1,55%
45	258.496.168	253.976.220	4.519.947	1,75%	54.239.369	1,75%
50	258.496.168	253.474.004	5.022.164	1,94%	60.265.965	1,94%
55	258.496.168	252.971.788	5.524.380	2,14%	66.292.562	2,14%
60	258.496.168	252.469.571	6.026.597	2,33%	72.319.158	2,33%
65	258.496.168	251.967.355	6.528.813	2,53%	78.345.755	2,53%
70	258.496.168	251.465.138	7.031.029	2,72%	84.372.351	2,72%
75	258.496.168	250.962.922	7.533.246	2,91%	90.398.948	2,91%
80	258.496.168	250.460.706	8.035.462	3,11%	96.425.544	3,11%
85	258.496.168	249.958.489	8.537.678	3,30%	102.452.141	3,30%
90	258.496.168	249.456.273	9.039.895	3,50%	108.478.737	3,50%
95	258.496.168	248.954.057	9.542.111	3,69%	114.505.334	3,69%
100	258.496.168	248.451.840	10.044.328	3,89%	120.531.930	3,89%

The Impact of CPP Tariffs on the Reduction of Cost of Generation

Furthermore, the analysis of the effectiveness of the implementation of Critical Peak Pricing (CPP) tariffs in reducing the Cost of Supply (BPP) of generation, which is also influenced by the percentage of load shifting by consumers. This table displays the value of BPP ToU per Month (Rp) for conditions without load shifting and after load shifting at various percentage levels (from 0% to 100%).

Specifically, this table measures "Savings per month (Rp)", "Savings per month (%)", "Savings per year (Rp)", and "Savings per year (%)" resulting from load shifting efforts. The data shows that an increase in the percentage of load shifting performed by consumers consistently results in a greater reduction in generation BPP. For example, at 0% shifting, no savings occur. However, when the load shifts reach 100%, there is a monthly BPP saving of IDR 69,392, which is equivalent to 0.31% per month or around IDR 832,700 per year. Although this percentage savings looks smaller compared to the ToU tariff scheme, it shows that the CPP Tariff also contributes to the operational efficiency of the electricity system by encouraging consumption reductions during critical peak periods.

The Impact of Implementing Dynamic Tariffs in Load Prediction

After proposing and integrating dynamic rates (such as Time-of-Use) into the machine learning model that we have created, we found that the predictions of the resulting electrical load undergo significant changes. By incorporating Time-of-Use (ToU) rates into the model, the predictions of subsequent electrical loads can change and adapt to more efficient price adjustments.

The ToU rates applied in the model allow load predictions to change dynamically according to the price patterns set for each period. This serves to maximize cost savings by shifting electricity consumption to periods with lower tariffs, as recommended by off-peak tariffs.

Machine learning models that were previously trained to predict electricity load based on historical data can now adjust predictions to changes in tariffs, leading consumers to consume electricity by the hour at a lower price. As a result, the predicted load generated reflects not only the energy consumption needs, but also the cost reduction strategies that customers can carry out by taking into account the variations in tariffs that apply throughout the day.

Thus, the dynamic rate approach applied to machine learning models not only affects load prediction, but also optimizes energy consumption based on more efficient rate patterns, providing more realistic estimates and directly correlating with potential cost savings.

Table 12. Comparison of actual load and flat rates against two prediction models, namely Random Forest (RF) and XGBoost with dynamic rates

Time	Flat Rate		ToU Rates with Random Forest		ToU Rates with XGBoost	
	Load (kWh)	Usage Fee (Rp)	Load (kWh)	Usage Fee (Rp)	Load (kWh)	Usage Fee (Rp)
Off Peak	291.171	494.853.547	353.635	489.297.448	354.306	490.361.185
Mid Day	258.946	440.086.950	240.773	435.465.760	241.230	436.738.491
On Peak	201.590	342.607.821	158.007	334.846.321	158.307	334.899.814
Total	**751.707**	**1.277.548.317**	**752.415**	**1.259.609.529**	**753.843**	**1.261.999.489**

The data presented above illustrates a comparison between the actual load and two prediction models, namely Random Forest (RF) and XGBoost (XG), along with the calculation of the cost generated based on the flat rate and the cost adjustment based on the dynamic rate (which is more expensive in the peak period).

In the Off Peak period, the actual load was recorded at 291,171 kWh with the cost of using a flat tariff of IDR 494,853,547. For the Random Forest (RF) model, the load prediction reaches 353,635 kWh, with the cost adjusted using a dynamic tariff of IDR 489,297,448. Meanwhile, the XGBoost (XG) model predicts a load of 354,306 kWh with an adjusted cost of IDR 490,361,185. Although the predictions show a slight increase in load, the difference between the cost of the flat rate and the charge with the dynamic rate shows the impact of energy use at more expensive peak hours.

In the Mid Day period, the actual load value is 258,946 kWh at a cost of IDR 440,086,950 using a flat tariff. The RF model shows a load prediction of 240,773 kWh at an adjusted cost of IDR 435,465,760, while the XG model estimates 241,230 kWh at a cost of IDR 436,738,491. In this period, despite a slight decline in predicted consumption, the cost adjustment to dynamic rates still reflects higher costs compared to flat rates.

For the On Peak period, the actual load was recorded at 201,590 kWh, at a cost of IDR 342,607,821 at the flat rate. The RF model predicts a load of 158,007 kWh with an adjusted cost using a dynamic tariff of IDR 334,846,321, while the XG model predicts 158,307 kWh at a cost of IDR 334,899,814. In this peak period, although predictions point to a decrease in energy consumption, higher dynamic rates make the total cost more expensive, especially during peak hours when higher rates are charged.

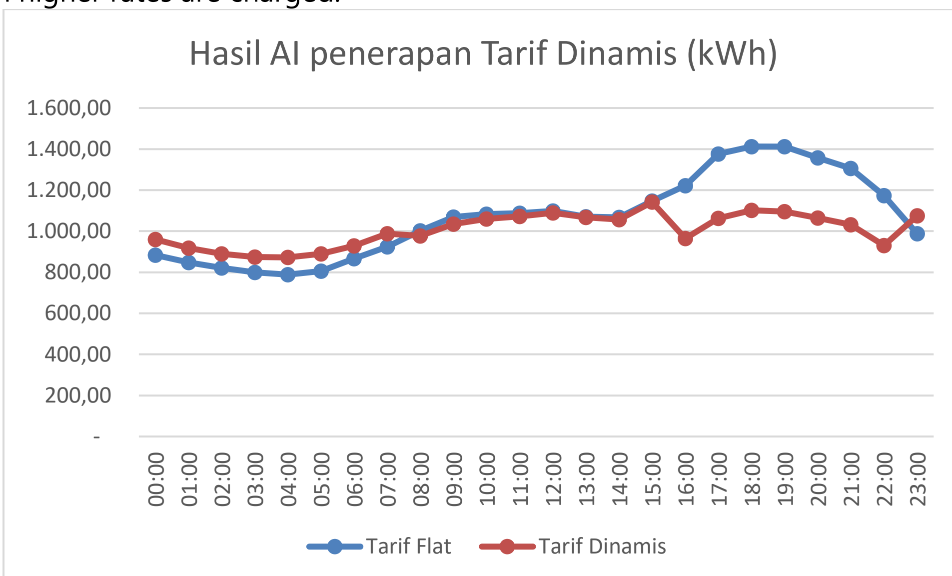

Figure 3. predicted energy consumption

The curve in Figure 3 shows a comparison of predicted energy consumption before and after dynamic tariffs are applied using machine learning. At dynamic rates, there is a reduction in energy consumption during peak hours (16:00–23:00), as well as an increase in consumption during hours with lower rates (23:00–08:00), suggesting that consumers can shift the burden to optimize costs. This is in line with the implementation of Advanced Metering Infrastructure (AMI), which enables real-time energy consumption data collection and more efficient dynamic tariff management. With AMI, PT PLN (Persero) can monitor expenses and adjust tariffs, thereby encouraging better energy management and reduced operational costs.

Overall, this data shows how dynamic rates affect the costs incurred by consumers. With higher rates in peak periods, even if there is an adjustment in energy consumption predicted by the model, the costs charged are still greater compared to the cost of using flat rates. The use of this prediction model can help consumers understand the impact of dynamic rates on their monthly costs, while also providing an incentive to shift their energy consumption to a cheaper time to reduce costs.

CONCLUSION

Based on the analysis, the use of machine learning models, particularly Random Forest and XGBoost, effectively predicts electrical loads with high accuracy, with XGBoost demonstrating a slight advantage in minimizing prediction errors and explaining data variability. The implementation of dynamic rates like Time-of-Use (ToU) tariffs successfully shifts electricity consumption from peak to non-peak periods, reducing operational costs and enhancing generation system efficiency, yielding 20-30% cost savings for consumers who adopt load shifting. The application of Advanced Metering Infrastructure (AMI) improves the precision of energy consumption data, enabling more accurate dynamic tariff design and real-time monitoring of usage. The study recommends combining ToU and Critical Peak Pricing (CPP) to better manage peak loads and incentivize consumers to shift demand, which can enhance long-term energy efficiency, reduce carbon emissions, and support the transition to a sustainable energy system. Future research should explore the integration of real-time renewable energy availability into dynamic pricing models and machine learning forecasts to further optimize load management and maximize the use of clean energy resources.

REFERENCES

Ahmad, A., Hassan, A., Gul, M., Saeed, S., Bukhari, A. A. A., & Khel, S. K. (2018). A review of demand response in an efficient smart grid environment. The Electricity Journal, 31(7), 55-63. https://doi.org/10.1016/j.tej.2018.07.014

Ahmad, A., Khan, A., Javaid, N., Hussain, H. M., Abdul, W., Almogren, A., Alamri, A., & Niaz, I. A. (2017). An optimized home energy management system with integrated renewable energy and storage resources. Energies, 10(4), 549. https://doi.org/10.3390/en10040549

Antonopoulos, I., Robu, V., Couraud, B., Kirli, D., Norbu, S., Kiprakis, A., Flynn, D., Elizondo-Gonzalez, S., & Wattam, S. (2020). Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review. Renewable and Sustainable Energy Reviews, 130, 109899. https://doi.org/10.1016/j.rser.2020.109899

Borenstein, S., & Holland, S. P. (2022). Electricity retail rate design in a decarbonizing economy: An analysis of time-of-use and critical peak pricing. MIT Center for Energy and Environmental Policy Research Working Paper, 2022-015.

Carroll, J., Lyons, S., & Denny, E. (2014). Reducing household electricity demand through smart metering: The role of improved information about energy saving. Energy Economics, 45, 234-243. https://doi.org/10.1016/j.eneco.2014.07.009

Jain, A., & Gupta, S. C. (2024). Evaluation of electrical load demand forecasting using various machine learning algorithms. Frontiers in Energy Research, 12, 1408119. https://doi.org/10.3389/fenrg.2024.1408119

Kaur, A., Nonnenmacher, L., & Coimbra, C. F. M. (2022). Energy forecasting in smart grid systems: Recent advancements in probabilistic deep learning. IET Generation, Transmission & Distribution, 16(22), 4461-4479. https://doi.org/10.1049/gtd2.12603

Khan, Z. A., & Jayaweera, D. (2020). Smart meter data based load forecasting and demand side management in distribution networks with embedded PV systems. IEEE Access, 8, 2631-2644. https://doi.org/10.1109/ACCESS.2019.2962987

Kumar, S., Singh, A., & Sharma, R. (2022). Optimised extreme gradient boosting model for short term electric load demand forecasting of regional grid system. Scientific Reports, 12, 19282. https://doi.org/10.1038/s41598-022-22024-3

Li, Y., Gao, W., Ruan, Y., Ushifusa, Y., & Yoshida, Y. (2018). Demand response of customers in Kitakyushu smart community project to critical peak pricing of electricity. Energy & Buildings, 168, 251-260. https://doi.org/10.1016/j.enbuild.2018.03.029

Makwarela, E., Shongwe, T., & Marwala, T. (2022). Leveraging Advanced Metering Infrastructure data for operational efficiency. Energy Informatics, 5(1), 1-18. https://doi.org/10.1186/s42162-022-00195-7

Moreno, M. V., Úbeda, B., Skarmeta, A. F., & Zamora, M. A. (2014). A survey on Advanced Metering Infrastructure. International Journal of Distributed Sensor Networks, 10(12), 414692. https://doi.org/10.1155/2014/414692

Paudyal, S., Cañizares, C. A., & Bhattacharya, K. (2015). Using smart meter data to improve the accuracy of intraday load forecasting considering customer behavior similarities. IEEE Transactions on Smart Grid, 6(2), 911-918. https://doi.org/10.1109/TSG.2014.2376879

Rasheed, M. B., Javaid, N., Ahmad, A., Khan, Z. A., Qasim, U., & Alrajeh, N. (2015). An efficient power scheduling scheme for residential load management in smart homes. Applied Sciences, 5(4), 1134-1163. https://doi.org/10.3390/app5041134

Siano, P. (2014). Demand response and smart grids—A survey. Renewable and Sustainable Energy Reviews, 30, 461-478. https://doi.org/10.1016/j.rser.2013.10.022

Ustun, T. S., Zayegh, A., & Ozansoy, C. (2024). Review on smart grid load forecasting for smart energy management using machine learning and deep learning techniques. IET Smart Grid, 7(3), 145-162. https://doi.org/10.1049/stg2.12089

Valencia-Salazar, I., Pinzón, D., & López-Lezama, J. M. (2021). A data analytics/big data framework for Advanced Metering Infrastructure data. Sensors, 21(16), 5650. https://doi.org/10.3390/s21165650

Yang, P., Tang, G., & Nehorai, A. (2013). A game-theoretic approach for optimal time-of-use electricity pricing. IEEE Transactions on Power Systems, 28(2), 884-892. https://doi.org/10.1109/TPWRS.2012.2207134

Zhang, Q., Wang, X., & Fu, M. (2021). Critical peak rebate strategy and application to demand response. Protection and Control of Modern Power Systems, 6(1), 1-12. https://doi.org/10.1186/s41601-021-00206-x

Zhang, Y., Chen, W., Xu, R., & Black, J. (2022). Load forecasting for energy communities: A novel LSTM-XGBoost hybrid model based on smart meter data. Energy Informatics, 5(1), 1-21. https://doi.org/10.1186/s42162-022-00212-9