AurovilleConsulting

Modelling Time of Use Electricity Tariffs for Tamil Nadu

October 2023

Sustainable Energy Transformation Series

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Acknowledgment

This publication forms a part of the Sustainable Energy Transformation, Tamil Nadu (SET-TN) series of documents and activities. SET-TN aims to facilitate higher clean energy deployment in the State by working with all stakeholders to find sustainable and equitable solutions. SET-TN is a collaborative initiative by Auroville Consulting (AVC), Consumer and Civic Action Group (CAG), and the World Resources Institute India (WRII).

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Executive Summary

Integration of renewable energy is crucial for India to meet its climate targets, including the goal of achieving net zero emissions by 2070. As the power sector is currently largely dependent on fossil fuel consumption, it is expected to witness a substantial increase in renewable energy integration in the near future in order to meet the county's climate ambitions. Additionally, India is projected to experience rising demand for electricity. To ensure grid stability in the future with a higher share of renewable energy in the energy mix, effective demand-side management strategies are essential. Tamil Nadu is a renewable energy leader, and it will increasingly require demand flexibility resources in order to facilitate the integration of a higher renewable energy share.

This report evaluates the impact of different time of use (ToU) tariff designs on key grid management parameters for the Tamil Nadu grid in the year 2024. The objective is to examine how the provision of static price signals in the form of ToU tariffs, prompts consumers to shift electricity demand to another time slot or reduce electricity usage and how this can facilitate the integration of a higher renewable energy share. 27 different ToU tariff designs were evaluated. A share of 17% wind energy and 11% solar energy on the total energy demand in 2024 was assumed for the ToU tariff design simulation. Key insights presented here may only apply to Tamil Nadu with its yearly energy demand peaking consistently in the early afternoon hours of April.

The results highlight the importance of optimally defining the time slots of peak and off-peak hours to reduce peak load instances and curtailment of renewables. Shifting the peak hours' time slot from the current 6:00h to 10:00h and 18:00h to 22:00h to the alternative 5:00h to 7:00h and 17:00h to 23:00h shows improvements in some key parameters such as a reduction in peak load instances on the gross and net load. Along with the shifting peak hours, introducing a tariff rebate during the solar energy generation hours (solar sponge) from 10:00h to 16:00h has shown to be effective in reducing peak load magnitudes and shifting peak hours. This will encourage consumers to distribute their load away from traditional peak hours, resulting in smoother load distribution throughout the day. This has significant implications for grid stability and reliability. It has been most effective in reducing the instances of negative load and lower load instances which can be equated with the need for curtailment. Adjusting the peak hour tariff and altering the peak hours will have noticeable effects on load distribution and peak load occurrences.

The results indicate that a 25% increase in peak-hour tariffs outperforms a more aggressive ToU tariff increase in the tune of 40%. It was found that a 40% increase in peak hour tariff may create new peak load instances in the hours before or after. Off-peak rebates of 5% and 10% were simulated for the late night and early morning hours it was found that their impact on key grid management parameters was negligible.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACEEE	– American Council for an Energy-Efficient Economy
BAU	– Business as Usual
CEA	– Central Electricity Authority
C&I	– Commercial and Industria
CUF	– Capacity Utilisation Factor
DSM	– Demand Side Management
EV	– Electric Vehicle
GW	– Gigawatt
HT	– High Tension
IT	– Information Technology
kWh	– Kilowatt Hour
LT	– Low Tension
MoP	– Ministry of Power
MNRE	– The Ministry of New and Renewable Energy
MU	– Million Units
MW	– Megawatt
MW/h	– Megawatt per hour
PEM	– Price eleasticity matrix
RPO	– Renewable Purchase Obligation
SLDC	– The State Load Dispatch Centre
TN	– Tamil Nadu
TNERC	– Tamil Nadu Electricity Regulatory Commission
ToU	– Time of Use

01 Introduction

India has pledged to achieve net zero emissions by the year 2070 (Rajya Sabha 2022) . Furthermore, the country has committed to promoting healthy and sustainable living as a key solution to combat climate change. To achieve this, India must adopt an environmentally sustainable, low-carbon approach in all major sectors of the economy. One of the key sectors that requires a rapid transformation to tackle climate change is the electricity sector. Though India is adding renewable energy capacity at a fast pace, the share of renewable energy in total electricity generation as of 2023 is still below 30%. Unlocking the required finances to accelerate the deployment of renewables along with the required power transmission and distribution infrastructure and finding solutions for legacy coal and lignite power plants are among the key challenges of this energy transition. The increasing need for flexibility services for the management is another urgent requirement. Grid flexibility services, enhance the capability of the grid operators to match generation with demand, and with an increasingly larger share of variable renewable energy sources this has become imperative. Introducing demand-side management measures such as time-of-use tariffs can be an effective and cost-efficient instrument to grid operators in facilitating the integration of renewables (IEEFA 2023).

Tamil Nadu, being one of the most industrialised states in India, is expected to witness a significant rise in the demand for electricity in the future. To meet the growing demand for electricity in the country's climate goals, the state must accelerate the transition towards a sustainable energy future. The state is endowed with excellent wind (on-shore and off-shore) and solar energy potential and has already made significant strides toward clean energy sources. Hence, Tamil Nadu stands out among most states in India, not just for its solar potential within the renewable energy sector but also for its onshore and offshore wind potential. As of the year 2023,17,225 MW or 51% of its installed power generation capacity is renewable (Energy Department of Tamil Nadu 2023). The state's solar capacity currently stands at 6,497 MW (MNRE 2023), with the state government aiming for another 20 GW of solar energy capacity by 2030 (PV Magazine 2020).

The integration of solar and wind energy into the power grid can yield network advantages such as lower peak loads, reduced transmission and distribution losses, and decreased cost of supply. Despite these benefits, concerns have been raised about the challenges of integrating solar and wind energy into the grid, including an increase in ramping up and ramping down rates. To mitigate these challenges, it is necessary to implement strategies such as time-of-use tariffs (ToU), incentives for solar energy consumption during peak solar generation hours, and the use of energy storage to store solar energy for later use.

Time-varying rates or ToU tariffs are recognised globally, as an important Demand Side Management (DSM) measure. ToU tariffs are typically used to reduce the demand on the system during peak hours. ToU tariffs reflect the time-varying nature of electricity costs more accurately when compared with flat rates. The cost of generating electricity can vary substantially over the course of the day and the year, but consumers have traditionally paid on the basis of flat-rate tariffs. The mismatch between the cost of supplying electricity at a particular time and the price of using it at that time leads to inefficiency. The effect of this inefficiency is compounded by the capital-intensive nature of electricity generation. Capacity is built to meet the highest load of the year, leading to the construction of generating capacity that operates only at partial capacity. Rather than charging consumers flat rate tariffs, ToU tariffs vary by the time of the day or by season. ToU rates can be static (i.e., the same every day) or dynamic (i.e., changing in response to system conditions). ToU tariffs give consumers an incentive to shift their electricity consumption from peak times to off-peak times, thereby providing energy cost-saving opportunities for the consumers and a reduction in overall power system costs to the utility (Citizensadvice 2020).

This report models the impacts of ToU tariffs, rebates, and changing time slots of the ToU tariffs on key grid management parameters such as peak load instances, minimum load instances, and ramping up and ramping down requirements. In the first part of this report, a load analysis with three different renewable energy scenarios for the year 2024 is undertaken. While all three renewable energy scenarios aim at meeting the Renewable Purchase Obligations (RPO) as of 29.91% (MoP 2022), the scenarios differ in their respective shares of wind and solar energy.

In the second part of the report, the more promising RE scenario, in terms of the utilised key grid management parameters, is then used to model various ToU tariffs. A total of 27 ToU tariff designs were modelled, out of these 3 ToU tariff designs were selected for a more detailed analysis. These 3 ToU tariff designs were selected as they promised to better facilitate higher RE integration in terms of reducing the need for curtailment, reducing gross and net load peak instances, and limiting ramping up and ramping down requirements.

02 Methodology

The following methodological steps were undertaken in modelling the impact of ToU tariff design on the net and gross power load of Tamil Nadu.

Figure 1: Methodological steps

For a detailed description of the methodology and underlying assumption used in the report refer to Annex 11.1 of this report.

03
Comparative Analysis

There is a pattern in the load profile across multiple years, with the peak yearly gross load occurring on an afternoon in the month of April.

In the year 2022, there was a notable rise in electricity demand compared to the preceding years 2020 and 2021, which were heavily impacted by the COVID-19 pandemic. The lockdown measures during the pandemic resulted in the closure of industrial and commercial units for a significant portion of those years, leading to a decrease in electricity demand. This is visible in Figure 2 for the year 2020. However, with the reopening of industrial and commercial sectors in 2022, the electricity demand experienced a significant increase, including a higher peak value. For this analysis, we conducted a load forecast for the year 2024, assuming a load increase of 14% from 2022 with the reopening of the industrial and commercial sectors (refer to Annex 11.1).

Over the 3 years, from 2020 to 2022, of load data available a consistent increase in the single highest recorded peak instance on the gross load can be observed. Also, the maximum peak instance on the gross load mostly occurs in the afternoon of April, this applies to the years 2021, 2022, 2023, and 2024 (refer to Table 1). In 2020, however, the maximum peak load occurred in March at 19:00h. This disparity can be attributed to the impact of the lockdown in 2020, which led to reduced demand from commercial and industrial consumers in April 2020. The highest recorded peak increased from 15,565 MW in 2020 to 17,516 MW in 2022 and is expected to reach 20,340 MW in 2024 (refer to Table 1).

Figure 2: Hourly gross load of Tamil Nadu for the years 2020, 2021, 2022 and 2024

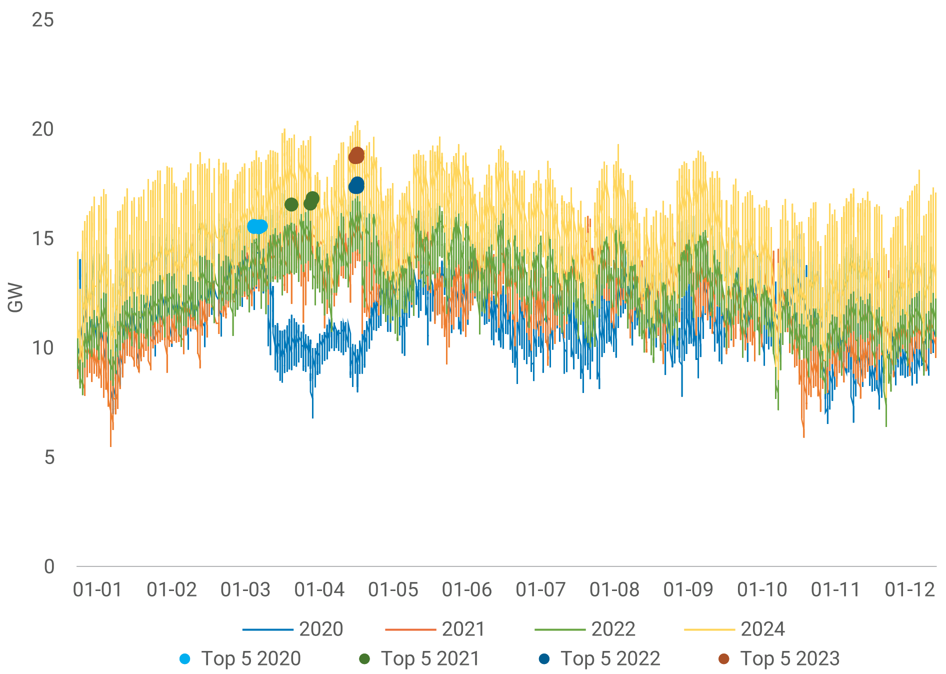


Figure 3: Hourly gross load of Tamil Nadu for selected months of the years 2020, 2021, 2022 and 2024 with the top for gross load peak instances

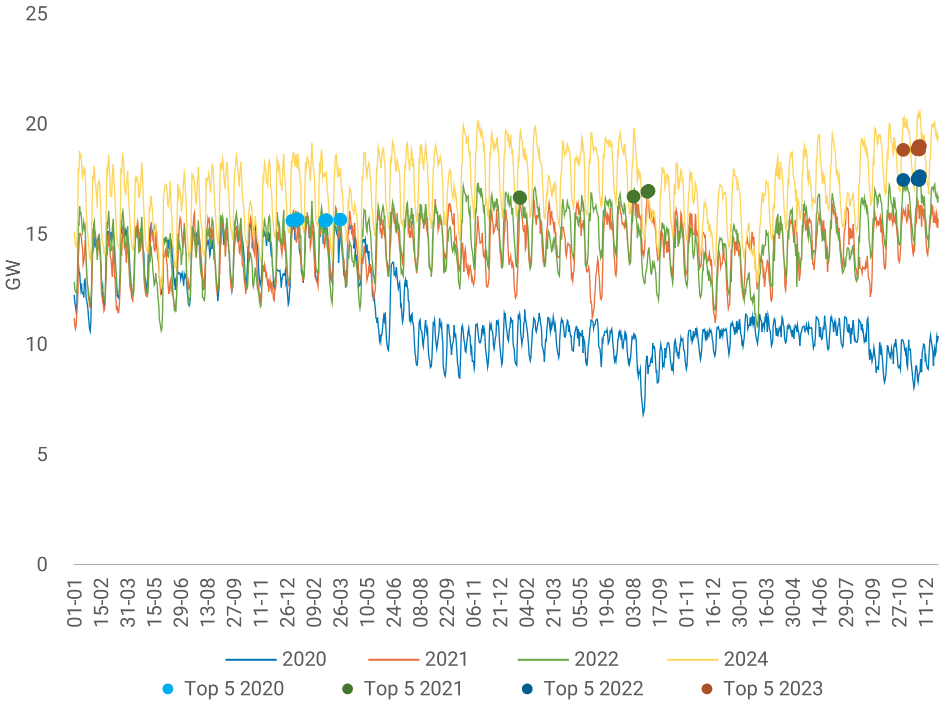


Table 1: Highest recorded peak and valley gross load instance with time stamps

Year	Timestamp	Peak (MW)	Timestamp	Lowest Valley (MW)
2020	2020-03-16 19:00	15,565	2020-11-15 05:00	6,518
2021	2021-04-10 12:00	16,845	2021-01-15 03:00	5,459
2022	2022-04-29 15:00	17,516	2022-12-10 04:00	6,394
2024	2024-04-27 13:00	20,340	2024-12-08 04:00	7,719

04

Modelling Various Renewable Energy Scenarios

The proportion of wind and solar energy in the renewable energy mix influences both the peak load and the frequency of ramping-up instances.

This chapter explores three different renewable energy scenarios for the year 2024. Further, the impact of these renewable energy scenarios on key grid management parameters such as peak load and ramping up requirements are modelled. The overall volume of renewable energy assumed for the year 2024 is determined based on the Renewable Energy Obligation (RPO)[1] for the year 2024. As per the Ministry of Power (MoP 2022), the RPO for the year 2024 is 29.91%. Based on the load forecast undertaken in the previous chapter, the RPO of 29.91% for the year 2024 represents 40,474 MU of renewable energy. To better understand the grid impact of solar energy and wind energy, three scenarios for meeting the RPO were simulated. The scenarios vary by percentage shares of solar and wind energy. Hydroenergy is expected to contribute 1.08% of the total RPO in 2024. Therefore, to meet the remaining RPO of 28.83%, or 39,013 MU of energy will need to come from wind and solar energy (refer to Table 2).

Table 2: Scenarios with different solar and wind energy shares

	Share on RPO (%)		Energy (MU)		Share on total generation (%)		Additional capacity requirement (MW)	
Scenario	**Solar**	**Wind**	**Solar**	**Wind**	**Solar**	**Wind**	**Solar**	**Wind**
RE Scenario 1	~60%	~40%	23,743	15,269	17.55%	11.28%	8,879	2,673
RE Scenario 2	~50%	~50%	19,733	19,280	14.58%	14.25%	6,699	4,308
RE Scenario 3	~40%	~60%	15,527	23,486	11.47%	17.36%	4,413	6,023

A CUF of 21% was assumed to determine the additional solar energy capacity requirement. To estimate the additional wind energy requirement a CUF of 28% was used.

The three scenarios were evaluated on two key parameters, which are (i) recorded instances in the upper (17,000 to 20,000 MW) net load peak range (refer to table 4) and (ii) instances of high ramping up and ramping down requirements (>1,500 MW/h) for the system's net load (refer to Table 3). The scenario that shows the highest instances of net peak load reduction and ramping up requirements will be analysed in more depth and utilised for the simulation of ToU tariffs in the later chapter.

Three ramping-up and down ranges, low (1,500 MW/h), medium (2,500 MW/h) and high (3,500 MW/h), are evaluated. Scenario 3 which has a relatively higher wind energy share shows a lower number of ramping up as well as ramping down instances in all three ranges (refer to Table 3 below). A higher share of wind energy than solar in the energy mix can ease the stress on existing generators to ramp up.

[1] As per the RPO, 29.91% of the total energy to be sourced should come from renewable sources. Out of this, wind energy commissioned after march 2022 is expected to contribute 2.46%, while hydro energy should contribute 1.08%. The remaining 26.37% of the RPO can be achieved through other renewable sources, which may include solar, existing wind, and other sources. In order to develop our cases, we have assumed that solar and wind energy would constitute this "Other RPO" of 26.37% at varying proportions and analysed their potential impacts on the total load for the year 2024.

Table 3: Ramping instances by scenario on net load

	Ramping up			Ramping down		
Scenario	**>1,500 MW/h**	**>2,500 MW/h**	**>3,500 MW/h**	**>1,500 MW/h**	**>2,500 MW/h**	**>3,500 MW/h**
RE Scenario 1	963	358	48	717	325	87
RE Scenario 2	848	198	9	596	224	32
RE Scenario 3	667	72	1	442	106	9

Additionally, the number of net peak load instances was evaluated. RE Scenario 3 shows the lowest occurrences in net load peak instances in the ranges of 17,000 MW - 18,000 MW, 18,000 MW - 19,000 MW, and 19,000 MW - 20,000 MW (refer to Table 4). RE Scenario 2 and 3 show a comparable number of net load instances in the lower ranges of -4,000 MW to 0 MW, 0 MW to 3,000 MW and 3,000 MW to 6,000 MW, whereas RE Scenario 1 shows the highest recorded instances in this ranges (refer to Table 5).

Table 4: Recorded instances in the top ranges of the net load

Scenario	17,000 – 18,000 MW	18,000 – 19,000 MW	19,000 – 20,000 MW
RE Scenario 1	160	65	10
RE Scenario 2	150	55	8
RE Scenario 3	142	47	8

Table 5: Recorded instances of lowest ranges in the net load

Scenario	-4,0000 - 0 MW	0 – 3,000 MW	3,000 – 6,000 MW
RE Scenario 1	32	275	734
RE Scenario 2	29	243	556
RE Scenario 3	27	249	581

The combination of solar and wind energy in the energy mix exhibits complementary characteristics. However, a slightly higher allocation of wind energy relative to solar energy, specifically with wind energy surpassing solar energy by 5.11%, yields improved outcomes . Based on these three grid management parameters, instances of high ramping-up and ramping down on the net load, and reduction of net load peak instances, the RE Scenario 3 yields better results. This scenario has the least ramping-up and ramping down instances in the >1,500 MW/h range and shows the lowest numbers of peak instances in the upper net load ranges, therefore scenario 3 has been selected for a more in-depth analysis and for the ToU tariff design modelling in the following sections.

05
Load Analysis

In this section an in-depth analysis of the selected RE scenario 3, that is, meeting the 29.91% of RPO by 2024 with 60% energy from wind and 40% energy from solar, is presented. Of the 29.91% of the RPO (or 39,013 MU), 11.47% (or 15,527 MU) of the total energy demand is sourced from solar and 17.36% (or 23,486) MU of total demand is sourced from wind. Furthermore, an in-depth analysis of the impact of solar and wind energy on various aspects of the energy system are undertaken. This includes quarterly solar and wind generation profiles. A net load analysis including frequency distribution changes and ramping up and ramping down requirements by quarters is undertaken. The findings provide insights into integrating renewable energy sources into the grid.

5.1. QUARTERLY SOLAR AND WIND GENERATION PROFILES

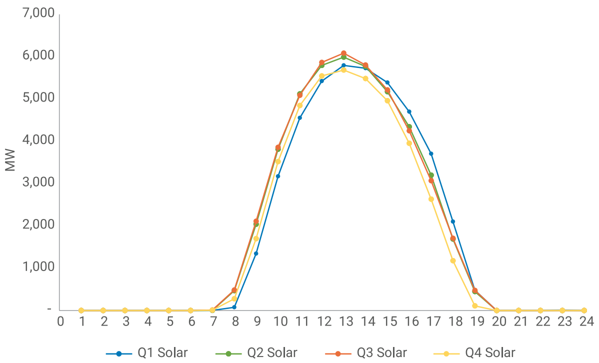
Solar generation remains consistent throughout the year across different quarters, whereas wind generation exhibits a stronger seasonal pattern with peak generation in the months from April to September.

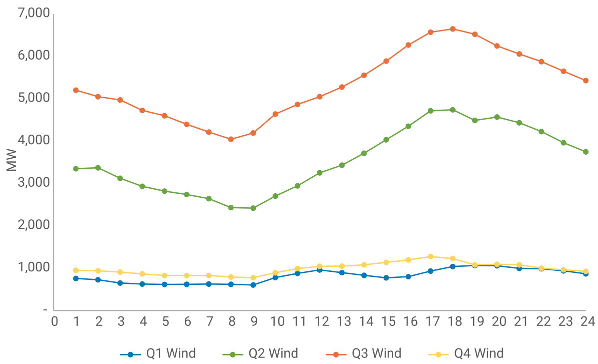
A quarterly load pattern analysis for 2024 is undertaken. The quarters are defined as Quarter 1 (January, February, March), Quarter 2 (April, May, June), Quarter 3 (July, August, September), and Quarter 4 (October, November, December). The forecasted daily average solar and wind generation profiles for each quarter of the year 2024 are presented below. Solar energy generation is highest in Quarter 2 and Quarter 3 while the peak wind generation occurs in the in Quarter 3 (refer to Table 6). It is found that solar generation consistently peaks at 13:00h across all quarters while wind energy peaks at 17:00h during the second and third quarters of the year (refer to Figure 4). Solar energy generation is most abundant during the daytime when sunlight is available, while wind energy generation is typically higher during the evening and night-time. This complementary nature allows for a more balanced and consistent energy supply throughout the day. By combining solar and wind power in an energy mix, the intermittency of one source can partially be compensated by the availability of the other energy source, resulting in a more reliable and stable renewable energy system.

Table 6: Quarterly share of annual solar and wind energy generation

	Q1	Q2	Q3	Q4
Solar energy	25%	26%	26%	24%
Wind energy	8%	33%	50%	9%

Figure 4: Quarterly solar and wind energy generation





5.2. IMPACT OF WIND ENERGY & SOLAR ENERGY ON LOAD

Solar energy has a more consistent impact on the load across all quarters of the year, while wind energy has a more significant impact during the third quarter.

For the year 2024, the net load values are calculated by subtracting the solar and wind generation from the gross load. The charts below represent the average daily load profiles for the gross load, gross load minus solar, gross load minus the wind, and net load for all quarters of the year 2024. The analysis shows that solar energy has a consistent impact on the load across all quarters of the year, while wind energy has a more significant impact during the third quarter.

Figure 5: Total load, Load minus solar, Load minus the wind, and the net load are plotted for all the quarters.

5.3 IMPACT OF SOLAR AND WIND ON FREQUENCY DISTRIBUTION

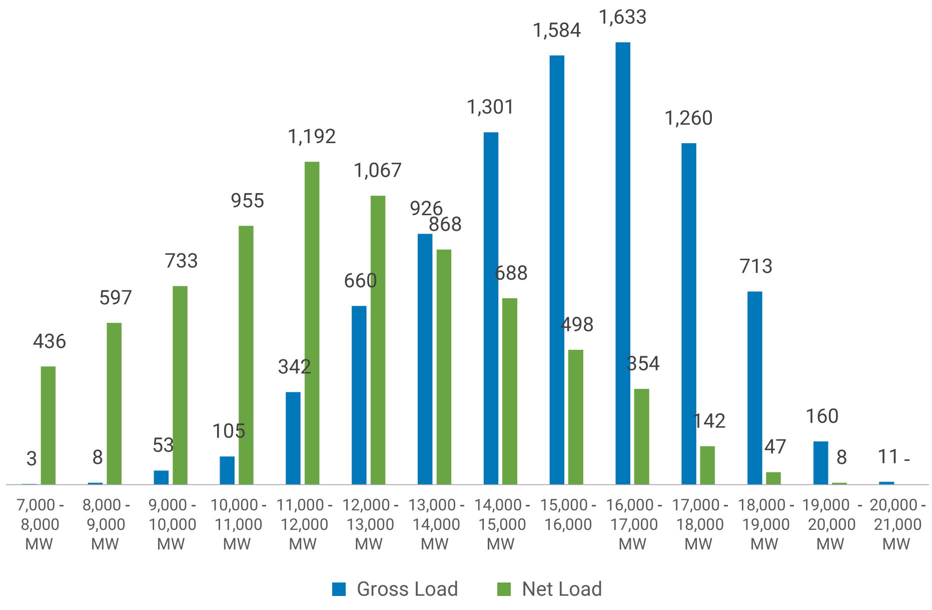
Both, solar and wind energy have a positive impact in reducing the frequency of high-load occurrences. A RE mix with a slightly higher share of wind energy is more effective in reducing the frequency of high-load occurrences.

Upper ranges of the load:

A plot was generated to show the number of instances where the gross load and net load fall into certain ranges. In higher ranges such as 13,000 MW – 21,000 MW, the results indicate a reduced number of instances for the net load as compared to the gross load, implying that solar energy and wind energy, both, have a positive impact in reducing the frequency of high load occurrences. For example, the instances of peak load in the range of 20,000 MW – 21,000 MW reduces from 110 in the gross load to 0 instances in the net load, this is a 100% reduction. While the instances of peak load in the range of 19,000 MW – 20,000 MW reduces from 160 in the gross load to 8 instances in the net load, representing a 95% reduction.

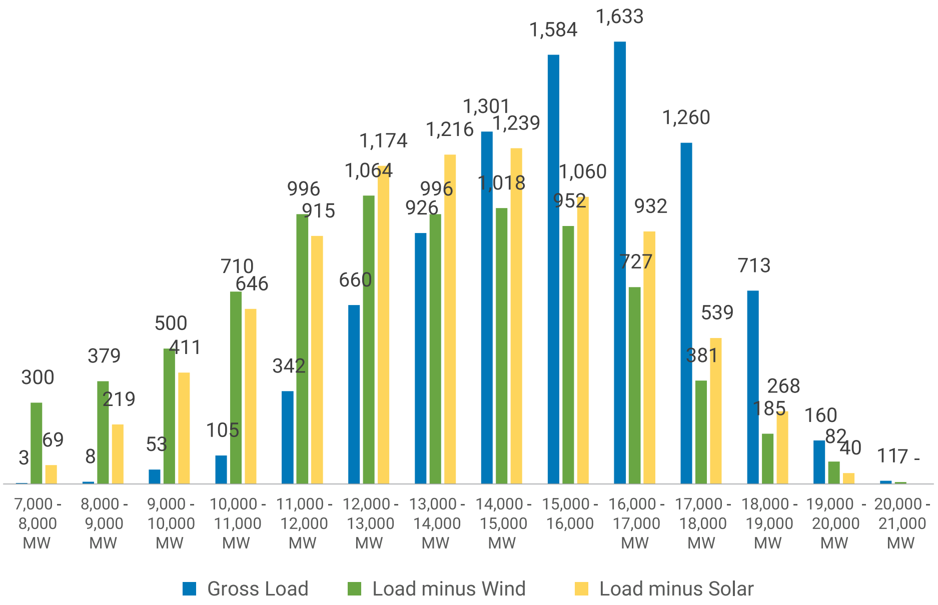
For the net load, an increase in recorded instances for the load range of 7,000 MW – 12,000 MW can be observed. This indicates that the reduced frequency of high load- levels in the top ranges due to solar and wind energy is shifted to the lower ranges.

Figure 6: Frequency distribution of the load and net load in the top ranges of the load levels.



Comparing the effects of solar and wind energy, it appears that the top 110 instances occurring between the load range of 20,000 MW to 21,000 MW are 100% reduced by solar, while wind reduced these top 110 instances to just 7 instances. However, the higher share of wind energy has a consistent impact on reducing the frequency of high-load levels in a broader range of 14,000 MW - 20,000 MW. In this range under the ‘load minus wind’ profile, the instances of 14,000 MW to 20,00MW are the lowest in comparison to the ‘load minus solar’. This suggests that while solar energy is more effective in reducing to the top load instance in the top load range of 20,000 MW to 21,000 MW, wind energy is more effective in reducing instances over a slightly wider high-load range than solar (refer to Figure 7).

Figure 7: Frequency distribution of the load in comparison to the load minus solar and load minus wind



The analysis delves into the consistency of observed trends across all four quarters of the year by segmenting the load frequency distribution accordingly. It aims to discern the impact of renewable energy on the load profile. Notably, gross load instances appear to be higher in quarters 1 and 2 compared to quarter 4, primarily due to reduced demand during the latter period. However, a significant transformation occurs in quarter 3, where renewable energy plays a role in reducing peak load instances to minimal levels, resulting in the net load instances between 20,000 MW and 21,000 MW effectively reducing to zero (refer to Figure 8). This trend remains consistent across all quarters, showcasing the efficacy of renewable energy in significantly reducing peak load occurrences within the 15,000 MW to 21,000 MW range, as depicted in Table 7. Quarter 3, in particular, stands out, demonstrating a substantial reduction in net load instances across various load ranges. Quarter 4 is the next best in terms of reducing instances since it is a period characterised by relatively low demand. The combination of renewable energy generation and low demand during this time results in fewer instances of net load in the upper load ranges. The findings suggest that renewable energy supply, especially wind rather than solar, significantly contributes to the reduction of net load instances, particularly during peak demand periods in quarter 3. This is observed in Figure 9, where the bars representing 'load minus wind' depict the gross load after subtracting the wind generation, leading to a reduction in gross load instances for quarter 3. Conversely, the observed reduction in quarter 4 appears to be influenced by both the low demand and renewable energy generation, culminating in fewer instances of net load in higher load ranges.

Figure 8: The frequency distribution of recorded instances of the load in the top ranges of the gross and net load by quarters

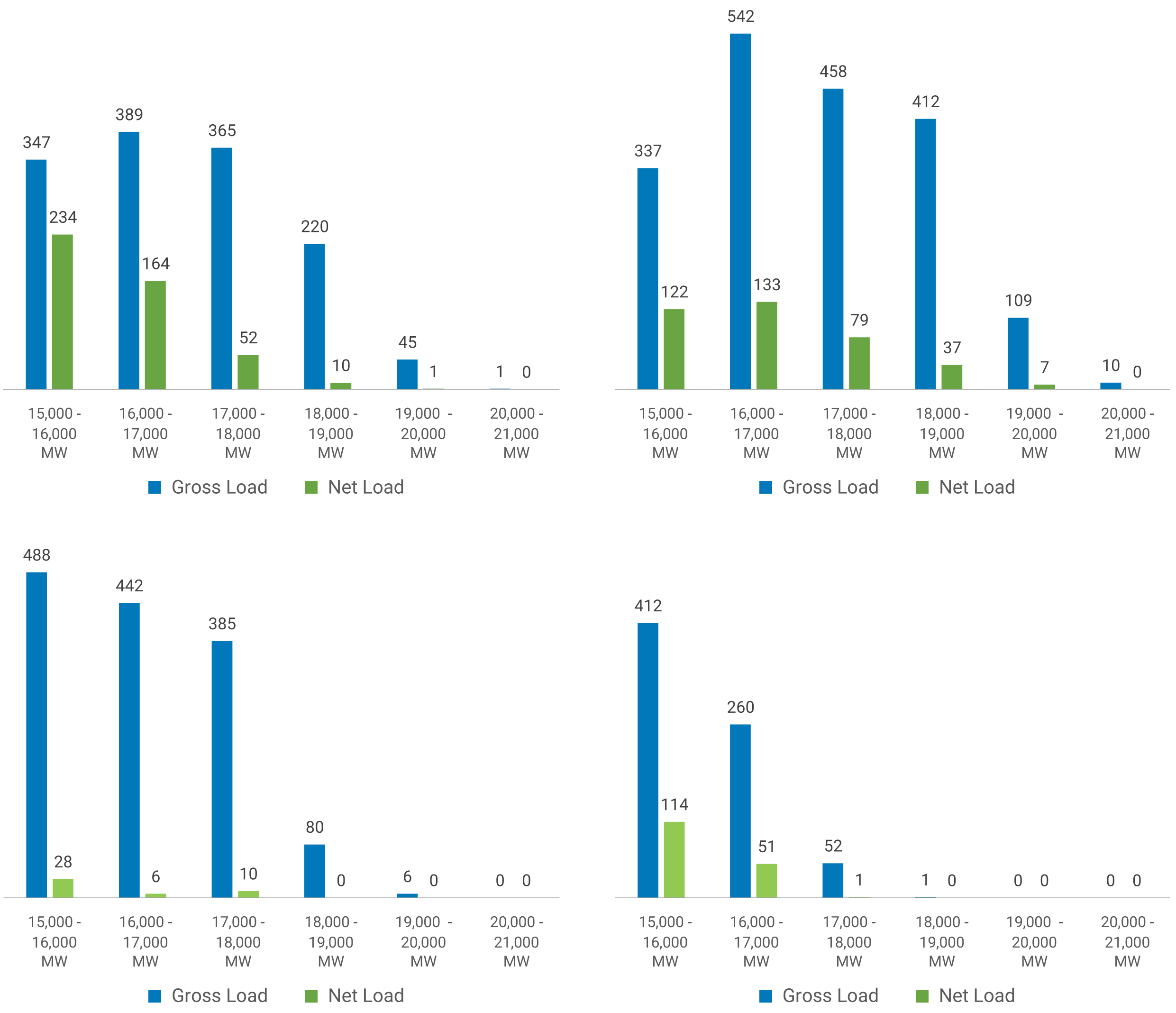
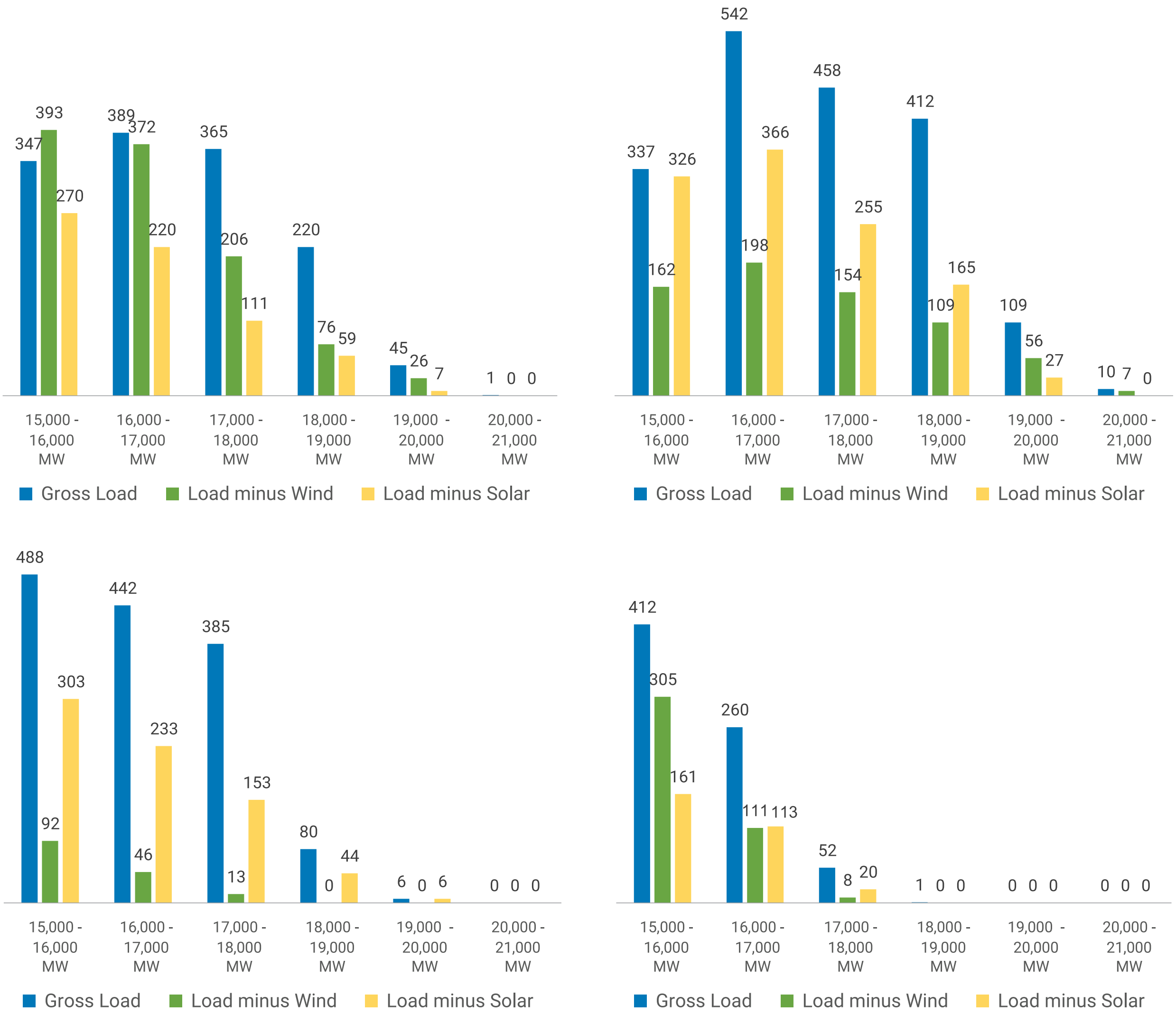


Table 7: Percentage reduction of the gross load due to renewable energy

Load range	Q1	Q2	Q3	Q4
15,000 - 16,000 MW	33%	64%	94%	72%
16,000 - 17,000 MW	58%	75%	97%	80%
17,000 - 18,000 MW	86%	83%	97%	98%
18,000 - 19,000 MW	95%	91%	100%	100%
19,000 - 20,000 MW	98%	94%	100%	100%
20,000 - 21,000 MW	100%	100%	100%	100%

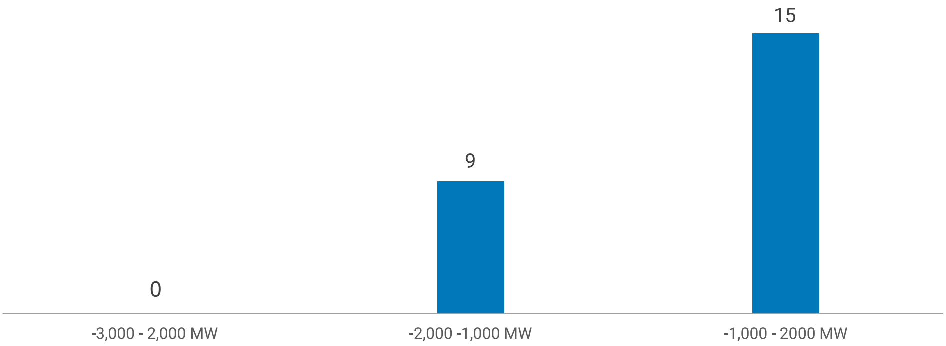
Figure 9: Recorded instances by load range on the gross load, load minus wind and load minus solar



Lower ranges of the load:

The analysis focuses on instances within the lower load ranges. Notably, there are no occurrences of gross load below 0 MW, and likewise, none for load minus solar or load minus wind in these lower ranges. However, there are instances of net load within the lower ranges, as illustrated in Figure 10. This can be attributed to the combined contribution of solar and wind energy, generating instances in the lower load levels. Optimising the utilization of solar and wind generation will result in reduced or even eliminated occurrences in the lower load ranges.

Figure 10: Frequency distribution instances of the net load in the lower ranges of the load levels



The frequency distribution of gross and net load instances within the ranges of 17,000 MW – 21,000 MW and 15,000 MW – 17,000 MW over the 24 hours of the day is illustrated in the Figures 11 and 12. It is evident that the number of net load instances is lower than that of the gross load across each of the 24 hours of the day. Solar and wind energy effectively caters to peak demand hours within the specified load ranges. However, it is important to highlight that there are still significant instances of load in higher ranges occurring during specific hours, namely 08:00h, 9:00h, 19:00h, 20:00h, and 21:00h, which demand special attention in order to minimise their occurrence.

Figure 11: Number of instances of the gross load occurring in the ranges of 17,000 MW – 21,000 MW and 15,000 MW – 17,000 MW by hour of the day.

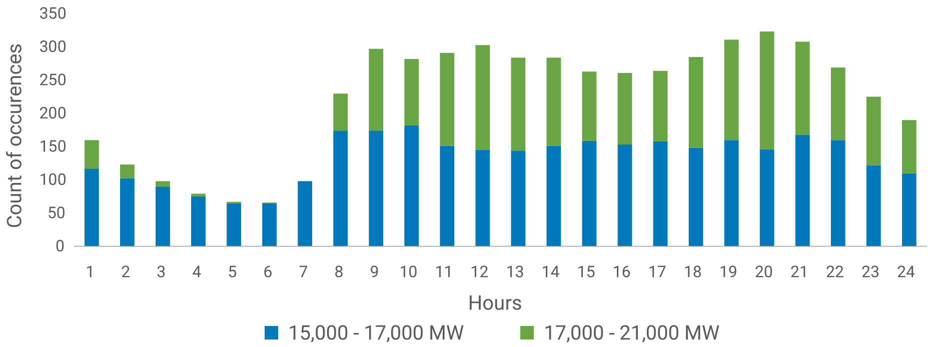
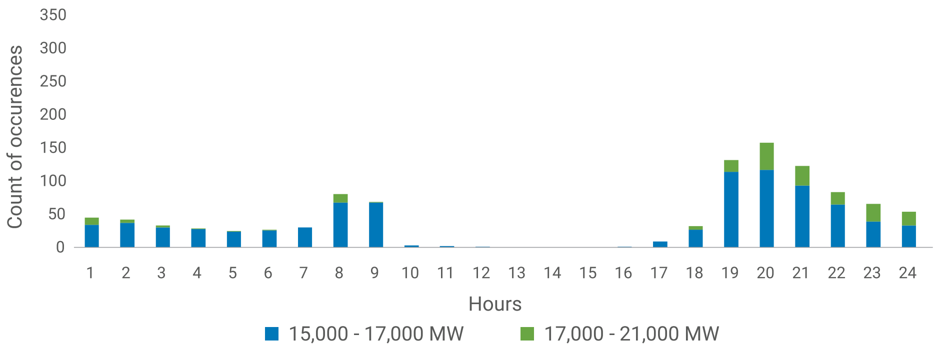


Figure 12 Number of instances of the net load occurring in the ranges of 17,000 MW – 21,000 MW and 15,000 MW – 17,000 MW by hour of the day.



5.4 RAMPING UP REQUIREMENTS

Integration of solar and wind energy into the system presents a technical challenge in terms of ramping up and down other energy sources.

In the case of gross load, the majority of ramping instances for the year 2024 are found to be below 1,500 MW/h, with only a few instances exceeding 2,500 MW/h (refer to Figure 13). However, the introduction of solar and wind energy significantly increased the count of higher ramping-up instances. In the net load, the magnitude of the ramping up and down instances increases, reaching up to 2,500 MW/h and even surpassing 3,500 MW/h (refer to Figure 14).

Figure 13:Ramping instances for the year 2024 on the gross load

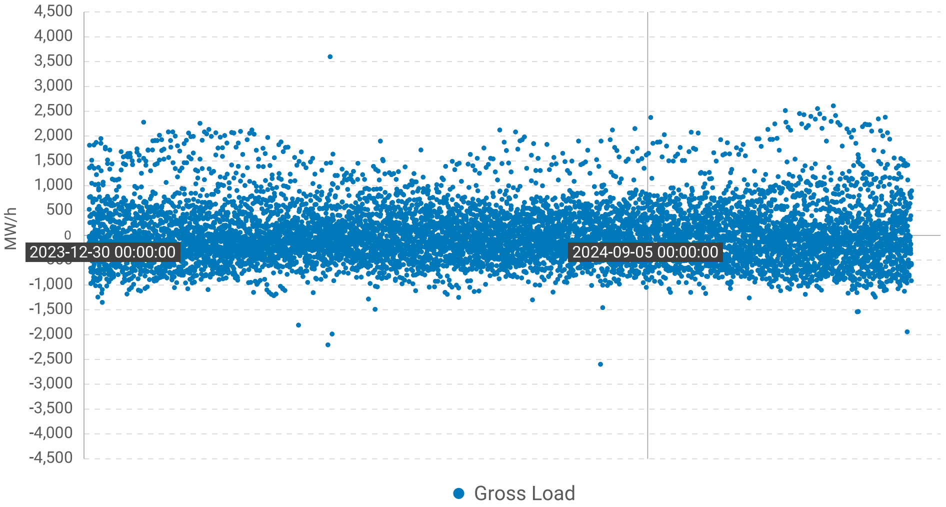
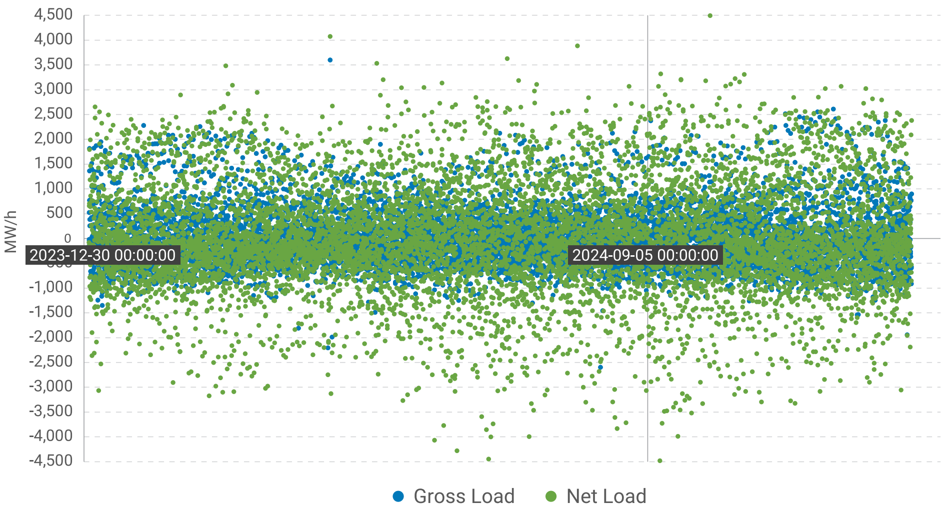


Figure 14:Ramping instances for the year 2024 on the gross and net load



To further assess ramping up and ramping down requirements for the year 2024, the load was divided into three categories: (i) load above and below 1,500 MW/h, (ii) load above and below 2,500 MW/h and iii) load above and below 3,500 MW/h. The net load exhibits a higher number of instances of ramping up as well as ramping down compared to the gross load (refer to Table 8). However, there is just an instance of ramping up above 3,500 MW/h on both the gross and the net load. This observation indicates that the integration of solar and wind energy into the system may present a technical challenge in terms of ramping up generation from conventional power plants.

Table 8: Ramping up and down instances above 1,500 MW/h, 2,500 MW/h and 3,500 MW/h for 2024

	Ramping up			Ramping down		
	> 1,500 MW/h	>2,500 MW/h	>3,500 MW/h	> 1,500 MW/h	>2,500 MW/h	>3,500 MW/h
Gross Load	217	4	1	7	1	0
Net Load	667	72	1	442	106	9

The number of instances of ramping up in 2024 above the thresholds of 1,500 MW/h, 2,500 MW/h, and 3,500 MW/h is analysed and plotted by each hour. The analysis shows a significant ramping up requirement for the gross load, specifically in the range above 1,500 MW/h, occurring at 07:00h (as shown in Figure 15: Left). This particular time corresponds to the morning peak. On the net load we observe instances where ramping up above 2,500 MW/h is necessary, particularly in the evening hours from 16:00h to 19:00h, while the ramping up requirements in the morning at 7:00h, remain similar to what was observed on the gross load (refer to Figure 15: Right).

When it comes to the ramping down instances, there are not many ramping down instances on the gross load. But there are ramping down instances on the net load starting at 9:00h and going on till 12:00h, which is attributed to the peak generation of solar.

Figure 15: Left: Ramping-up on gross load above 1,500 MW/h, 2,500 MW/h, and 3,500 MW/h. Right: Ramping-up on net load above 1,500 MW/h, 2,500 MW/h and 3,500 MW/h

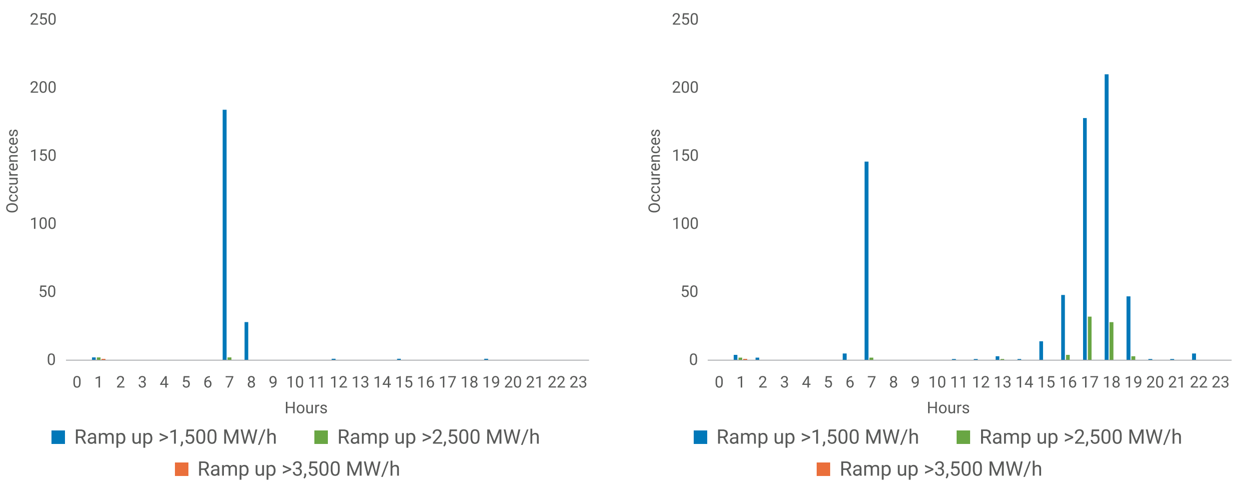
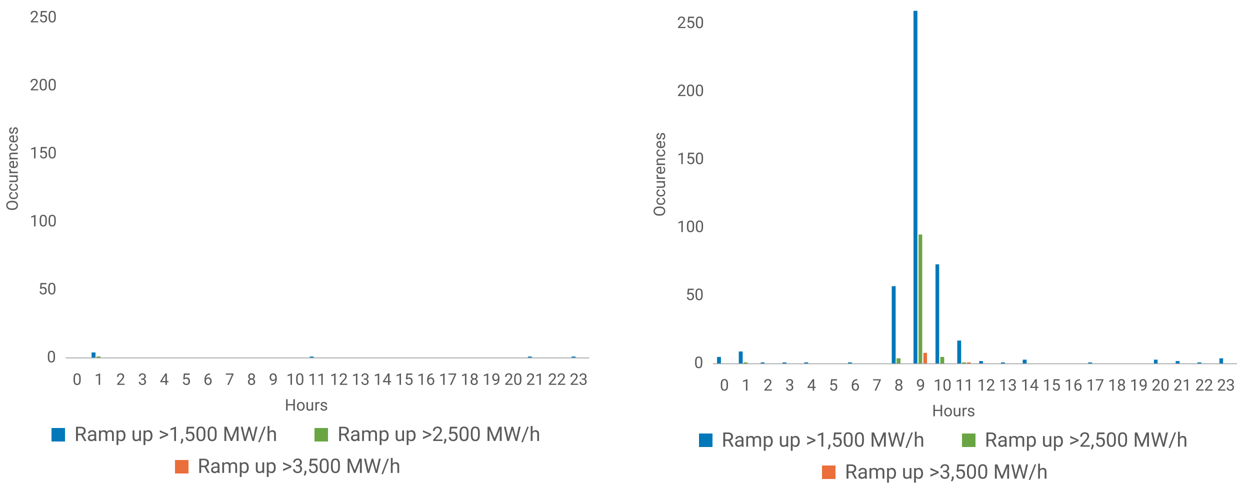


Figure 16: Left: Ramping-down on gross load above 1,500 MW/h, 2,500 MW/h, and 3,500 MW/h. Right: Ramping-down on net load above 1,500 MW/h, 2,500 MW/h and 3,500 MW/h



06

Simulating The Impact of Time Of Use Tariffs

In the following chapter 27 different ToU tariff scenarios are presented. These ToU scenarios differ along 5 variables. These are:

i. Variation in the peak hour tariff increase (0%, 25% and 40%).

ii. Variation in the off-peak hour tariff rebate (0%, 5%, and 10%).

iii. Variation the time slots assigned for peak hours (6:00h to 10:00h, 18:00h to 22:00h or 5:00h to 7:00h, 17:00h to 23:00h).

iv. Variation the time slots assigned for off- peak hours (22:00h to 5:00h or 0:00h to 5:00h).

v. Solar sponge: a tariff rebate of 20% during the main solar energy generation hours (10:00h to 15:00h).

The peak tariff rate determines the cost of electricity during peak hours, while the rebate offers a discount on the electricity consumed at certain hours called the off-peak hours. Peak and off-peak hours define the time periods during which the peak tariff rate and the rebate (off-peak tariff) apply, respectively. Furthermore, the 'solar sponge' refers to a tariff rebate that is meant to encourage solar energy consumption, avoid curtailment of solar power plants, and reduce the need for energy storage systems. A detailed listing of the ToU scenarios is provided below (refer to Table 9).

Table 9: Details of simulated ToU tariff scenarios

	Peak tariff increase	Off-peak tariff rebate	Peak hours	Off-peak hours	Solar Sponge	Comment
S1	0%	0%	N/A	N/A	No	No ToU tariffs
S2	25%	0%	6:00h to 10:00h 18:00h to 22:00h	22:00h to 5:00h	No	Peak and off-peak hour time slots as is currently the case in Tamil Nadu.
S3	40%	0%			No	
S4	0%	5%			No	
S5	25%	5%			No	
S6	40%	5%			No	
S7	0%	10%			No	
S8	25%	10%			No	
S9	40%	10%			No	
S10	0%	0%	N/A	N/A	No	Change in peak and off-peak hour time slots.
S11	25%	0%	5:00h to 7:00h 17:00h to 23:00h	0:00h to 5:00h	No	
S12	40%	0%			No	
S13	0%	5%			No	
S14	25%	5%			No	
S15	40%	5%			No	
S16	0%	10%			No	
S17	25%	10%			No	
S18	40%	10%			No	
S19	0%	0%	N/A	N/A	10:00h to 16:00h tariff reduction of 20%	Change in peak and off-peak hour time slots and the introduction of a tariff rebate at 20% during the main solar energy generating hours from 10:00h to 16:00h.
S20	25%	0%	5:00h to 7:00h 17:00h to 23:00h	0:00h to 5:00h		
S21	40%	0%				
S22	0%	5%				
S23	25%	5%				
S24	40%	5%				
S25	0%	10%				
S26	25%	10%				
S27	40%	10%				

The main parameters on which these ToU tariffs are evaluated are the recorded instances of:

i. gross load peak events (20,000 MW - 23,000 MW).

ii. net load peak events (18,000 MW - 21,000 WW).

iii. net load valley events (-5,000 MW – 0 MW).

iv. net load ramping up instances of higher magnitude (>2,500 MW/h).

v. net load ramping down instances of higher magnitude (>2,500 MW/h).

A selected number of ToU scenarios, that indicate the capacity to facilitate a smoother grid-integration of wind and solar energy will be analysed in depth in the later part of this chapter. The ToU scenarios selected for this will need to meet the following criteria: (i) they should not create higher gross load peak instances, (ii) reduce net load peak instances, (iii)shift loads to prime renewable energy generation hours and (iv) contain ramping up and ramping down instances on the net load.

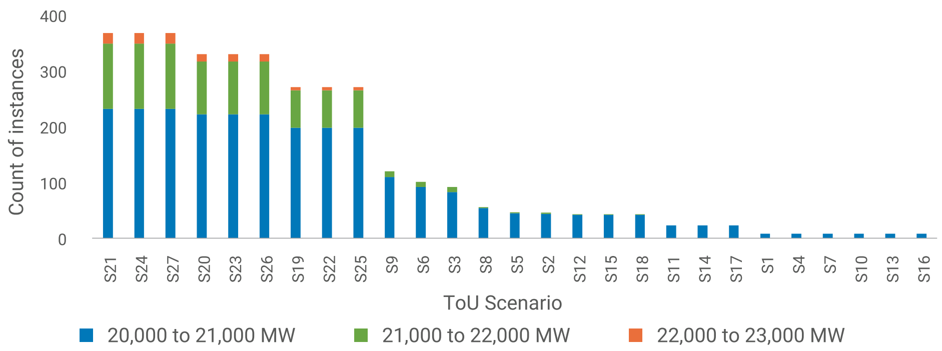
6.1 THE GROSS LOAD PEAK EVENTS

ToU tariffs with a solar sponge increases peak load instances and peak load magnitude on the gross load.

It is found that the scenario without any ToU tariff (S1) does not show any instances in the top gross load range from 22,000 to 23,000 MW and from 21,000 to 22,000 MW. The same scenario also shows one of the lowest number of instances in the gross load range from 20,000 to 21,000 MW. Further, it is found that ToU scenarios (S4, S7, S10, S13, S16) without any tariff increase for peak hours and with tariff rebates during off-peak hours in the of 0%, 5% and 10% and without a 'solar sponge' has the same count of peak gross load instances as the no ToU (S1) scenario.

The introduction of a 'solar sponge' and a tariff rebate of 20% during peak solar energy generation hours from 10:00h to 16:00h (S19 to S27) substantially increases the instances and magnitude of high gross peak load. Under these scenarios, gross peak load instances exceed the 22,000 MW threshold. This finding may be particular to Tamil Nadu's load profile which typically has a high demand and high gross load peak instances during the late morning and early afternoon. The introduction of the solar sponge will create additional demand in these hours, thereby increasing the recorded instances in the upper gross load range. Similarly, though less pronounced, the scenarios with a change in the peak and off-peak hour time slots and a peak hour tariff increase of 40% (S3, S6, and S9) also show an increase of gross peak load instances.

Figure 17: Recorded instances of peak for the gross load in the upper ranges by ToU scenario



6.2 GROSS LOAD PEAK INSTANCES BY HOURS OF OCCURRENCE

Redefining the time slots for peak and off-peak hours can increase peak load instances during solar energy generation hours.

Under the 'No ToU' scenario (S1) the instances of peak load in the gross load range of 20,000 to 23,000 MW occur between 11:00h and 15:00h. Introducing a peak hour tariff of +40% without a change in the time slots allocated for peak hours results in the occurrence of peak instances at 18:00h and 23:00h and also increases the instances recorded during 11:00h and 15:00h.

Changing the time slot allocation of peak and off-peak hours and introducing the 'solar sponge' results in an increase in recorded peak load instances between 11:00h and 15:00h. As this is a prime solar energy generation hour, this could be desirable outcome. Low-cost solar energy is available during these hours and if this energy is sourced from distributed solar energy systems, the stress on the transmission system can be mitigated. Assuming that the occurrence of peak instances during solar energy generation hours is desirable, then the single most impactful intervention is redefining the time slots for peak and off-peak hours, and introducing the 'solar sponge', e.g., an off-peak hour with tariff rebate during peak solar energy generation hours.

Figure 18:Gross load instances by ToU Scenario in the upper ranges of 20,000-23,000 MW distributed by hour of occurrences

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S1	0	0	0	0	0	0	0	0	0	0	0	3	1	2	1	1	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	18	13	4	1	1	2	5	2	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0	0	34	21	8	3	2	3	9	11	0	0	0	0	1
S4	0	0	0	0	0	0	0	0	0	0	0	3	1	2	1	1	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	0	0	0	18	13	4	1	1	2	5	2	0	0	0	0	1
S6	0	0	0	0	0	0	0	0	0	0	0	34	21	8	3	2	3	9	11	0	0	0	0	10
S7	0	0	0	0	0	0	0	0	0	0	0	3	1	2	1	1	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0	0	0	0	18	13	4	1	1	2	5	2	0	0	0	0	10
S9	0	0	0	0	0	0	0	0	0	0	0	34	21	8	3	2	3	9	11	0	0	0	0	29
S10	0	0	0	0	0	0	0	0	0	0	0	3	1	2	1	1	0	0	0	0	0	0	0	0
S11	0	0	0	0	0	0	0	0	0	0	1	6	1	2	1	3	3	6	0	0	0	0	0	0
S12	0	0	0	0	0	0	0	0	0	0	3	8	1	2	3	4	7	15	0	0	0	0	0	0
S13	0	0	0	0	0	0	0	0	0	0	0	3	1	2	1	1	0	0	0	0	0	0	0	0
S14	0	0	0	0	0	0	0	0	0	0	1	6	1	2	1	3	3	6	0	0	0	0	0	0
S15	0	0	0	0	0	0	0	0	0	0	3	8	1	2	3	4	7	15	0	0	0	0	0	0
S16	0	0	0	0	0	0	0	0	0	0	0	3	1	2	1	1	0	0	0	0	0	0	0	0
S17	0	0	0	0	0	0	0	0	0	0	1	6	1	2	1	3	3	6	0	0	0	0	0	0
S18	0	0	0	0	0	0	0	0	0	0	3	8	1	2	3	4	7	15	0	0	0	0	0	0
S19	0	0	0	0	0	0	0	0	0	0	0	61	57	44	33	37	39	0	0	0	0	0	0	0
S20	0	0	0	0	0	0	0	0	0	0	0	79	57	44	36	54	59	1	0	0	0	0	0	0
S21	0	0	0	0	0	0	0	0	0	0	0	86	57	44	45	60	71	5	0	0	0	0	0	0
S22	0	0	0	0	0	0	0	0	0	0	0	61	57	44	33	37	39	0	0	0	0	0	0	0
S23	0	0	0	0	0	0	0	0	0	0	0	79	57	44	36	54	59	1	0	0	0	0	0	0
S24	0	0	0	0	0	0	0	0	0	0	0	86	57	44	45	60	71	5	0	0	0	0	0	0
S25	0	0	0	0	0	0	0	0	0	0	0	61	57	44	33	37	39	0	0	0	0	0	0	0
S26	0	0	0	0	0	0	0	0	0	0	0	79	57	44	36	54	59	1	0	0	0	0	0	0
S27	0	0	0	0	0	0	0	0	0	0	0	86	57	44	45	60	43	6	0	0	0	0	0	0

S1 No ToU

S2 to S9
The introduction of a peak hour tariff for the time slots from 06:00 h -10:00 h and 18:00h h - 22:00h h along with an off-peak hour's rebates may result in the occurrences of gross load peak instances at night at 23:00 h. It also increases the recorded gross load peak instances during 11:00 h and 12:00h and 16:00h to 18:00h.

S10 to S18
The change in the off-peak and peak hours slots to 5:00 h -7:00h and 17:00h to 23:00h can result in a removal of gross load peak instances at 23:00 h in the 20,000-22,000 MW range that occur in S2 to S9. However new net load peak instances at 10:00 are recorded.

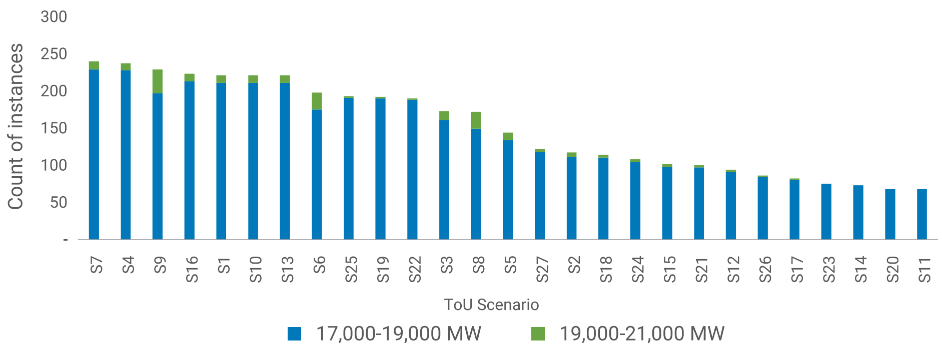
S19 to S27
A change in peak and off-peak hours, along with the Introduction of the ‚solar sponge', increases gross load peak instances during sunshine hours from 11:00 h to 17:00 h.

6.3 NET LOAD PEAK INSTANCES

There is a significant reduction in peak instances on the net load through change in peak and off-peak hours.

Assigning a new time slot to peak and off-peak results in a significant reduction on the higher ranges or recorded net load instances. For some simulated ToU scenarios (S11, S14, S20, S23) no peak load instances in the 19,000 to 21,000 MW ranges are recorded. The common denominator of these scenarios is a redefinition of peak and off-peak hours, and a peak hour tariff increase of 25%. The expected reduction of peak load instances and the magnitude of reduction of 2,000 MW for these scenarios is significant as this can add the grid-integration of a higher share of solar energy and may also reduce the overall power purchase cost.

Figure 19: Recorded instances of load in the upper ranges of the net load by ToU scenario



6.4 NET LOAD PEAK INSTANCES BY HOURS OF OCCURENCES

Well-defined peak and off-peak tariff times slots mitigate evening and night net load peak instances in the 19,000 MW – 21,000 MW range.

The simulated ToU scenarios with a tariff rate increase of 25% during peak hours, a change in the time slots for the off-peak and peak hours, have the potential to remove all net peak load instances in the 19,000 to 21,000 MW range (e.g., S, 11, S13, S20, S23) that are present in S1 during 19:00h to 21:00h.

Figure 20: Net load instances by hour of occurrence in the upper net load ranges of 19,000-21,000 MW

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	1	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3
S3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	6
S4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	2	1	0	0
S5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	6
S6	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	14
S7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	1	1	0	4
S8	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	14
S9	6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	18
S10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	1	0	0
S11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S12	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	1	0	0
S14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S15	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	1	0	0
S17	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S18	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
S20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S21	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
S23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S24	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
S26	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S27	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

S1 No ToU

S2 to S9
The introduction of a peak hour tariff for 6:00 h to 10:00 h and 18:00 h to 22:00h h, shifts the instances of evening peaks recorded from 19:00 h to 21:00 h to the hours before (18:00 h) and after (23:00 h to 0 h).

S10 to S18
The change in the off-peak and peak hours slots from 06:00 h -10:00 h and 18:00 h - 22:00h h to 5:00 h -7:00 h and 17:00 h - 23:00 h can result in a removal of net load peak instances in the 19,000-21,000 MW range.

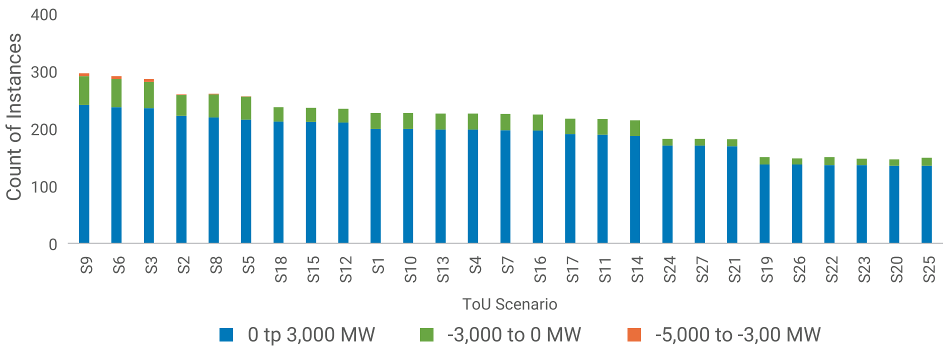
S19 to S27
A change in peak and off-peak hours along with the introduction of the 'solar sponge' results in the removal of recorded evening net peak load instances if compared with S2 to S9. Some scenarios such as S20 and S23 do not record a single instance.

6.5 NET LOAD VALLEY INSTANCES

Solar sponge reduces the need for solar energy curtailment.

The introduction of peak hours tariffs from 6:00h to 10:00h (S9, S6, S3, S8, S5, S2) may results in net load instances below -3,000 MW. The combination of changing the morning peak hours' time slots to 05:00h - 07:00h and the introduction of the 'solar sponge', and a tariff rebate of 20%, from 10:00h- 15:00h helps to reduce the net load instances in the negative and lower ranges significantly, no instances in the range of -3,000 to -5,000 MW and a reduced number of instances in the ranges from -3,000 to 0 MW and 0 to 3,000 MW are found.

Figure 21: Recorded load instances in the lower ranges of the net load by ToU scenario



6.6 NET LOAD VALLEY INSTANCES BY HOURS OF OCCURENCES

Solar sponge reduces the negative net load occurrences.

Introducing peak hours tariffs in the morning hours either from 06:00h to 10:00h (S2 to S9) or from 05:00h to 07:00h may create a moderate number of net load instances in the lower ranges of -5,000 to 0 MW as compared to the 'No ToU' scenario (S1). This is specifically pronounced with the 06:00h to 10:00h morning hour peak time slot, that shows a significant increase in net load instances in these lower ranges at 10:00h, indicating that this time slot for morning peak hour does not aid the integration of solar energy. A change in peak and off-peak hours, combined with the introduction of the solar sponge (S19 to S27) reduce the instances in the lower net load range particularly so from 10:00h to 15:00h.

Figure 22: Net load instances by hour of occurrence in the lower net load ranges of -5,000 MW to 0 MW

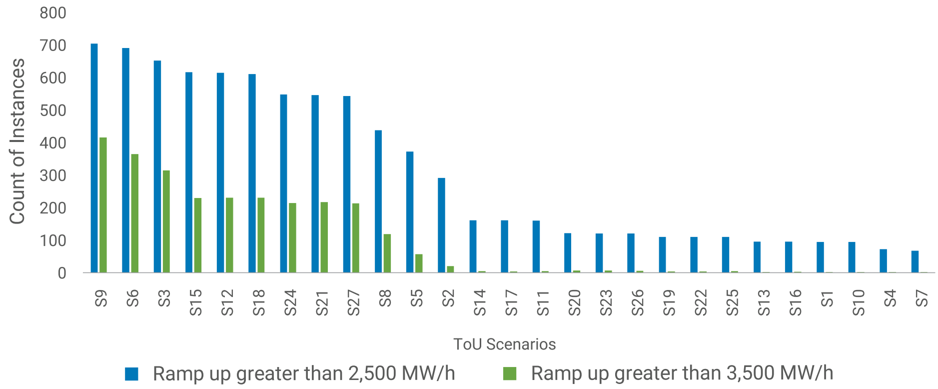
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
S1	0	0	0	0	0	0	0	0	0	0	5	5	4	6	6	2	0	0	0	0	0	0	0	0	**S1 No ToU**
S2	0	0	0	0	0	0	0	0	0	4	13	4	4	5	5	2	0	0	0	0	0	0	0	0	**S2 to S9** Introducing peak hours tariffs for 6:00 h to 10:00 h and 18:00 h to 22:00h increases the instances of net load occurrences on the lower ranges of -5,000 to 0 MW. This is especially prominent at 10:00 h.
S3	0	0	0	0	0	0	0	0	1	6	28	3	3	4	4	2	0	0	0	0	0	0	0	0	
S4	0	0	0	0	0	0	0	0	0	0	5	5	4	6	6	2	0	0	0	0	0	0	0	0	
S5	0	0	0	0	0	0	0	0	0	5	16	4	4	5	5	2	0	0	0	0	0	0	0	0	
S6	0	0	0	0	0	0	0	1	2	7	28	3	3	4	4	2	0	0	0	0	0	0	0	0	
S7	0	0	0	0	0	0	0	0	0	0	5	5	4	6	6	2	0	0	0	0	0	0	0	0	
S8	0	0	0	0	0	0	0	0	0	5	16	4	4	5	5	2	0	0	0	0	0	0	0	0	
S9	0	0	0	0	0	0	0	1	2	8	28	3	3	4	4	2	0	0	0	0	0	0	0	0	
S10	0	0	0	0	0	0	0	0	0	0	5	5	4	6	6	2	0	0	0	0	0	0	0	0	**S10 to S19** If compared to S1, the no ToU scenario, changing the time slots for peak hours in the morning to 5:00h to 7:00h and in the evening to 17:00h to 23:00h has no impact on the instances of low net load occurrences.
S11	0	0	0	0	0	0	1	0	0	0	5	4	4	6	5	2	0	0	0	0	0	0	0	0	
S12	0	0	0	0	0	0	1	0	0	0	4	4	4	6	4	1	0	0	0	0	0	0	0	0	
S13	0	0	0	0	0	0	0	0	0	0	5	5	4	6	6	2	0	0	0	0	0	0	0	0	
S14	0	0	0	0	0	0	1	0	0	0	5	4	4	6	5	2	0	0	0	0	0	0	0	0	
S15	0	0	0	0	0	0	1	1	0	0	4	4	4	6	4	1	0	0	0	0	0	0	0	0	
S16	0	0	0	0	0	0	0	0	0	0	5	5	4	6	6	2	0	0	0	0	0	0	0	0	
S17	0	0	0	0	0	0	1	0	0	0	5	4	4	6	5	2	0	0	0	0	0	0	0	0	
S18	0	0	0	0	0	0	1	1	0	0	4	4	4	6	4	1	0	0	0	0	0	0	0	0	
S19	0	0	0	0	0	0	0	0	0	1	6	2	2	2	0	0	0	0	0	0	0	0	0	0	**S20 to S21** The introduction of the solar sponge along with the change in the time slots for peak and off-peak hours removes all net load instances in the -5,000 to 0 MW range.
S20	0	0	0	0	0	0	1	0	0	0	5	1	2	2	0	0	0	0	0	0	0	0	0	0	
S21	0	0	0	0	0	0	1	1	0	0	5	1	2	2	0	0	0	0	0	0	0	0	0	0	
S22	0	0	0	0	0	0	0	0	0	2	6	2	2	2	0	0	0	0	0	0	0	0	0	0	
S23	0	0	0	0	0	0	1	0	0	0	5	1	2	2	0	0	0	0	0	0	0	0	0	0	
S24	0	0	0	0	0	0	1	1	0	0	5	1	2	2	0	0	0	0	0	0	0	0	0	0	
S25	0	0	0	0	0	0	0	0	0	2	6	2	2	2	0	0	0	0	0	0	0	0	0	0	
S26	0	0	0	0	0	0	1	0	0	0	5	1	2	2	0	0	0	0	0	0	0	0	0	0	
S27	0	0	0	0	0	0	1	1	0	0	5	1	2	2	0	0	0	0	0	0	0	0	0	0	

6.7 NET LOAD RAMPING UP INSTANCES

High ramping up instances can be reduced by ToU tariffs.

Scenarios with either no tariff increase during peak hours or with an increase in tariff of 25% along with a change in the time slots allocated for peak and off-peak hours show no ramping-up requirement in the range of 3,500 MW/h and above, they also have the lowest instances of ramping up requirement above the 2,500 MW/h range. All scenarios with a peak hour tariff increase of 40% in particular show a higher need for ramping up in the 3,500 MW/h and 2,500 MW ranges.

Figure 23: Ramping up instances on net load by ToU scenario



6.8 NET LOAD RAMPING UP INSTANCES BY HOURS OF OCCURENCE

Solar sponge reduces ramping up instances during afternoon hours.

For S1 (no ToU) the ramping up instances greater than 2,500 MW/h are concentrated in the morning at 07:00h and in the evening hours from 16:00h to 19:00h. Introducing peak hour tariffs from 06:00h to 10:00h and from 16:00h to 22:00h is expected to create significant ramping up instances in the range of 2,500 MW/h and greater during morning hours at 11:00h and during night-time, specifically at 23:00h (S2 to S9). This is less pronounced with the peak hour tariff increase of 0% and 25%. The change in the off-peak and peak hours slots from 06:00h -10:00h and 18:00h - 22:00h to 5:00h – 7:00h and 17:00h - 23:00h shifts the intensity of ramping up instances to 8:00h in the morning and 0:00h at night. However, the need for ramping up during the morning hours (07:00h) and evening hours (16:00h - 19:00h) can be reduced if compared to S1.

Figure 24: Ramping up instances in the range of 2,500 MW/h and greater on net load by ToU scenario

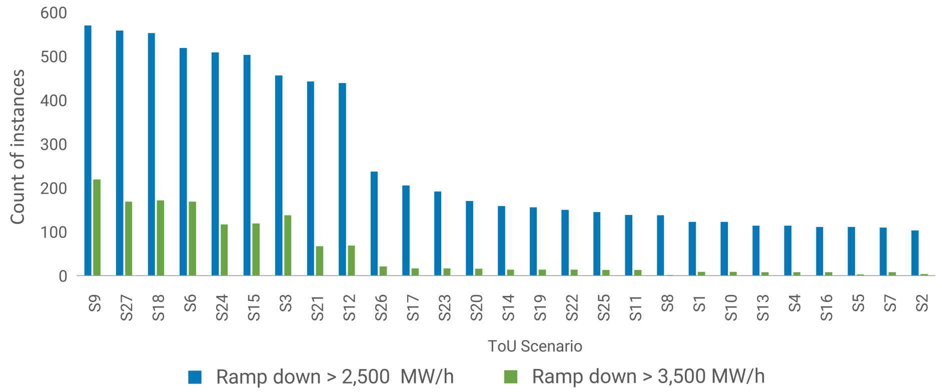
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
S1	0	4	0	0	0	0	0	24	0	0	0	0	0	1	0	0	2	24	31	11	0	0	0	0	**S1 No ToU**
S2	0	3	0	0	0	0	0	0	0	0	0	92	0	1	0	0	6	44	55	0	0	0	0	110	**S2 to S9** The introduction of a peak hour tariff creates additional instances of ramping-up requirements of 2,500 MW/h and greater during 11:00 h and 23:00 h.
S3	0	2	0	0	0	0	0	0	0	0	0	347	0	1	0	0	6	58	83	0	0	0	0	469	
S4	0	4	0	0	0	0	0	3	0	0	0	0	0	1	0	0	2	24	31	9	0	0	0	0	
S5	0	4	0	0	0	0	0	0	0	0	0	95	0	1	0	0	6	44	55	0	0	0	0	224	
S6	0	3	0	0	0	0	0	0	0	0	0	350	0	1	0	0	6	58	83	0	0	0	0	555	
S7	0	4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	24	31	8	0	0	0	0	
S8	0	4	0	0	0	0	0	0	0	0	0	100	0	1	0	0	6	44	55	0	0	0	0	347	
S9	0	3	0	0	0	2	0	0	0	0	0	350	0	1	0	0	6	58	83	0	0	0	0	617	
S10	0	4	0	0	0	0	0	24	0	0	0	0	0	1	0	0	2	24	31	11	0	0	0	0	**S10 to S18** The change in the off-peak and peak hours slots from 06:00 h -10:00 h and 18:00 h to 22:00h h to 5:00 h – 7:00 h and 17:00 h - 23:00 h may result in new peak instances occurring during 0:00 h and 8:00 h, while it could remove peak instances during 18:00h and 11:00 h.
S11	57	4	0	0	0	0	0	3	45	0	0	0	0	1	0	0	6	45	0	4	0	0	0	0	
S12	462	2	0	0	0	0	0	1	310	0	0	0	0	1	0	1	6	62	0	0	0	0	0	0	
S13	0	5	0	0	0	0	0	24	0	0	0	0	0	1	0	0	2	24	31	11	0	0	0	0	
S14	55	5	0	0	0	0	0	3	47	0	0	0	0	1	0	0	6	45	0	4	0	0	0	0	
S15	455	5	0	0	0	0	0	1	315	0	0	0	0	1	0	1	6	62	0	0	0	0	0	0	
S16	0	6	0	0	0	0	0	24	0	0	0	0	0	1	0	0	2	24	31	11	0	0	0	0	
S17	53	5	0	0	0	0	0	4	47	0	0	0	0	1	0	0	6	45	0	4	0	0	0	0	
S18	446	5	0	0	0	0	0	1	320	0	0	0	0	1	0	1	6	62	0	0	0	0	0	0	
S19	0	4	0	0	0	0	0	12	0	0	0	33	0	1	0	0	4	0	45	15	0	0	0	0	**S19 to S27** Change in peak and off-peak hours along with the Introduction of the ‚solar sponge' results along with a 25% peak hours tariff increase results in an overall reducing of ramping up instances in the >2,500 MW/h particularly so during the afternoon hours from 16:00 h to 19:00 h.
S20	57	4	0	0	0	0	0	2	32	0	0	19	0	1	0	0	8	0	0	6	0	0	0	0	
S21	462	2	0	0	0	0	0	1	268	0	0	14	0	1	0	1	14	0	0	0	0	0	0	0	
S22	0	5	0	0	0	0	0	11	0	0	0	33	0	1	0	0	4	0	45	15	0	0	0	0	
S23	55	5	0	0	0	0	0	2	32	0	0	19	0	1	0	0	8	0	0	6	0	0	0	0	
S24	455	5	0	0	0	0	0	1	271	0	0	14	0	1	0	1	14	0	0	0	0	0	0	0	
S25	0	6	0	0	0	0	0	11	0	0	0	33	0	1	0	0	4	0	45	15	0	0	0	0	
S26	53	5	0	0	0	0	0	2	33	0	0	19	0	1	0	0	8	0	0	6	0	0	0	0	
S27	446	5	0	0	0	0	0	1	274	0	0	14	0	1	0	1	14	0	0	0	0	0	0	0	

6.9 NET LOAD RAMPING DOWN INSTANCES

High peak hour tariffs may result in increased ramping down instances.

ToU scenarios with a peak hour tariff increase of 40% consistently show a higher ramping down requirement in the 2,500 MW/h and greater range. The only two scenarios for which no ramping does instances on the net load greater than 3,500 MW/h has been recorded are S2, S5 and S8, these are the scenarios with 25% increase in peak hour tariff and with peak hour time slots from 06:00h to 10:00h and 18:00h to 22:00h.

Figure 25: Ramping down instances on net load by ToU scenario



6.10 NET LOAD RAMPING DOWN INSTANCES BY HOURS OF OCCURENCE

The need for ramping down is consistently high at 9:00h across all ToU scenarios.

Under the no ToU scenario (S1) the highest number of ramping down instances above 2,500 MW/h are recorded in the morning slots from 08:00h to 11:00h, but particularly so at 09:00h. With the introduction of ToU tariffs we observe that higher instances of ramping down above 2,500 MW/h on the net load are emerging either during 07:00h and 19:00h (S2 to S8) or during 06:00h and 18:00h (S10 to S27). While to solar sponge may facilitate the higher grid integration of solar energy it will require more ramping down of the other generation fleets.

Figure 26: Ramping down instances in the range of 2,500 MW/h and greater on net load by ToU scenario

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S1	0	1	0	0	0	0	0	0	6	101	22	1	0	0	0	0	0	0	0	0	0	0	1	0
S2	1	3	0	0	0	0	0	2	1	69	9	0	1	0	0	0	0	0	0	21	0	0	0	0
S3	1	3	0	0	0	0	0	133	1	51	3	0	2	0	0	0	0	0	0	400	0	0	0	0
S4	0	3	0	0	0	0	0	0	6	101	22	1	0	0	0	0	0	0	0	0	0	0	1	0
S5	1	3	0	0	0	0	0	7	1	69	9	0	1	0	0	0	0	0	0	21	0	0	0	0
S6	1	3	0	0	0	0	0	202	1	51	3	0	2	0	0	0	0	0	0	400	0	0	0	0
S7	0	3	0	0	0	0	0	0	6	101	22	1	0	0	0	0	0	0	0	0	0	0	1	0
S8	1	3	0	0	0	0	0	19	1	69	9	0	1	0	0	0	0	0	0	21	0	0	0	0
S9	1	3	0	0	0	0	0	273	1	51	3	0	2	0	0	0	0	0	0	400	0	0	0	0
S10	0	1	0	0	0	0	0	0	6	101	22	1	0	0	0	0	0	0	0	0	0	0	1	0
S11	0	3	0	0	0	0	6	0	0	101	22	1	1	0	0	0	0	0	2	0	0	0	0	0
S12	0	3	0	0	0	0	134	0	0	101	22	1	1	0	0	0	0	0	33	0	0	0	0	0
S13	0	0	0	0	0	0	0	0	6	101	22	1	0	0	0	0	0	0	0	0	0	0	1	0
S14	0	1	0	0	0	0	16	0	0	101	22	1	1	0	0	0	0	0	2	0	0	0	0	0
S15	0	2	0	0	0	0	220	0	0	101	22	1	1	0	0	0	0	0	33	0	0	0	0	0
S16	0	0	0	0	0	0	0	0	6	101	22	1	0	0	0	0	0	0	0	0	0	0	1	0
S17	0	0	0	0	0	0	63	0	0	101	22	1	1	0	0	0	0	0	2	0	0	0	0	0
S18	0	0	0	0	0	0	319	0	0	101	22	1	1	0	0	0	0	0	33	0	0	0	0	0
S19	0	1	0	0	0	0	0	0	9	125	26	0	1	0	0	0	0	7	0	0	0	0	1	0
S20	0	3	0	0	0	0	10	0	0	130	30	0	1	0	0	0	0	6	6	0	0	0	0	0
S21	0	3	0	0	0	0	187	0	0	133	30	0	2	0	0	0	0	5	150	0	0	0	0	0
S22	0	0	0	0	0	0	0	0	8	122	25	0	1	0	0	0	0	7	0	0	0	0	1	0
S23	0	1	0	0	0	0	40	0	0	127	28	0	1	0	0	0	0	6	6	0	0	0	0	0
S24	0	1	0	0	0	0	310	0	0	130	28	0	2	0	0	0	0	5	150	0	0	0	0	0
S25	0	0	0	0	0	0	1	0	8	117	23	0	1	0	0	0	0	7	0	0	0	0	1	0
S26	0	0	0	0	0	0	98	0	0	120	27	0	1	0	0	0	0	6	6	0	0	0	0	0
S27	0	0	0	0	0	0	419	0	0	125	27	0	2	0	0	0	0	5	150	0	0	0	0	0

S1 No ToU

S2 to S9
The introduction of a peak hour tariff creates significant additional requirement of ramping down instances during morning hours (7:00 h) and evening hours (19:00h). These hours each lay one hours before the respective peak hour time slot.

S10 to S18
Compared to S2 to S9, the change in the off-peak and peak hours slots from 06:00 h -10:00 h and 18:00 h - 22:00h h to 5:00 h – 7:00 h and 17:00 h - 23:00 h has significantly reduced ramping down instances in the evening. It further shifted the time of these morning and evening ramping down instances by one hours prior for each.

S19 to S27
Change in peak and off-peak hours along with the Introduction of the ‚solar sponge' does not alter the ramping down requirements if compared to S10 to S18.

6.11 THE HIGHEST GROSS AND NET PEAK EVENTS

The single highest gross and net peak events occur in the month of April.

The table below lists the single highest instance for the selected evaluation parameters by ToU Scenario along with a time stamp that indicates the occurrence of this instance. The single highest gross peak and net peak event for all ToU Scenarios are at the end of April. While the time of the day at which the single highest gross peak occurs varies between morning hours (11:00h) and afternoon (13:00h and 15:00h) and early evening hours (17:00h), the single highest net load peak instances are found either in the evening hours (18:00h and 21:00h) or night hours (23:00h, 0:00h and 01:00h). All ToU scenarios with the solar sponge appear to reduce the single lowest net load instances (valley) recorded, an indication that the solar sponge facilitates a higher solar energy integration. The lowest net load instances across all simulated ToU scenarios are all recorded for the month of September. The single highest ramping up instance per ToU scenario are either recorded during late morning hours at 11:00h or in the night hours at 23:00h, 0:00h and 01:00h, these instances are recorded at different months (April, May, June, September). The single highest ramping down instance among the simulated ToU scenarios seems to be a result of the +40% peak hour tariff rate increase (S12, S15, S18, S21, S24, S27).

Figure 27: Single highest recorded instances by time of occurrence

Scenario	Timestamp Peak - Gross Load	Peak - Gross Load (MW)	Timestamp Peak - Net Load	Peak - Net Load (MW)	Timestamp Valley – Net Load	Lowest Valley – Net Load (MW)	Timestamp Peak Ramping Up Net Load	Peak Ramping Up Net Load (MW/h)	Timestamp Peak Ramping Down Net Load	Peak Ramping Down Net Load (MW/h)
S1	04-27 13:00	20,288	04-26 21:00	19,464	09-09 11:00	(2,755)	04-18 01:00	4,108	04-16 09:00	4,506
S2	04-27 11:00	21,104	04-26 18:00	19,554	09-09 10:00	(3,372)	10-05 11:00	4,870	04-16 09:00	4,520
S3	04-27 11:00	21,618	04-26 18:00	20,050	09-09 10:00	(4,351)	10-05 11:00	6,555	03-19 19:00	5,105
S4	04-27 13:00	20,288	04-26 21:00	19,339	09-09 11:00	(2,755)	04-18 01:00	4,195	04-16 09:00	4,492
S5	04-27 11:00	21,104	04-26 23:00	19,676	09-09 10:00	(3,401)	10-05 11:00	4,906	04-16 09:00	4,506
S6	04-27 11:00	21,618	04-26 23:00	20,148	09-09 10:00	(4,380)	05-04 23:00	6,718	03-19 19:00	5,144
S7	04-27 13:00	20,288	04-26 23:00	19,338	09-09 11:00	(2,755)	04-18 01:00	4,282	04-16 09:00	4,478
S8	04-27 11:00	21,104	04-26 23:00	20,125	09-09 10:00	(3,429)	05-04 23:00	5,474	04-16 09:00	4,492
S9	04-27 11:00	21,618	04-26 23:00	20,597	09-09 10:00	(4,408)	05-04 23:00	7,294	03-19 19:00	5,183
S10	04-27 13:00	20,288	04-26 21:00	19,464	09-09 11:00	(2,755)	04-18 01:00	4,108	04-16 09:00	4,506
S11	04-26 17:00	20,696	04-27 00:00	18,791	09-09 11:00	(2,609)	04-18 01:00	4,092	04-16 09:00	4,503
S12	04-26 17:00	21,200	04-27 00:00	19,251	09-09 11:00	(2,522)	06-03 00:00	5,558	05-04 18:00	6,329
S13	04-27 13:00	20,288	04-26 21:00	19,423	09-09 11:00	(2,755)	04-18 01:00	4,558	04-16 09:00	4,491
S14	04-26 17:00	20,696	04-28 01:00	18,788	09-09 11:00	(2,609)	04-18 01:00	4,542	04-16 09:00	4,489
S15	04-26 17:00	21,200	04-27 00:00	19,176	09-09 11:00	(2,522)	06-03 00:00	5,549	05-04 18:00	6,329
S16	04-27 13:00	20,288	04-26 21:00	19,381	09-09 11:00	(2,755)	04-18 01:00	5,008	04-16 09:00	4,477
S17	04-26 17:00	20,696	04-28 01:00	19,223	09-09 11:00	(2,609)	04-18 01:00	4,993	06-30 06:00	4,492
S18	04-26 17:00	21,200	04-28 01:00	19,566	09-09 11:00	(2,522)	06-03 00:00	5,541	05-04 18:00	6,329
S19	04-27 13:00	22,249	04-26 21:00	19,464	09-09 10:00	(2,197)	10-05 11:00	4,335	04-16 09:00	4,640
S20	04-27 15:00	22,645	04-27 00:00	18,791	09-09 10:00	(1,912)	10-05 11:00	4,159	04-16 09:00	4,638
S21	04-27 15:00	22,902	04-27 00:00	19,251	09-09 10:00	(1,740)	06-03 00:00	5,558	05-04 18:00	6,149
S22	04-27 13:00	22,249	04-26 21:00	19,423	09-09 10:00	(2,197)	04-18 01:00	4,558	04-16 09:00	4,626
S23	04-27 15:00	22,645	04-28 01:00	18,788	09-09 10:00	(1,912)	04-18 01:00	4,542	04-16 09:00	4,623
S24	04-27 15:00	22,902	04-27 00:00	19,176	09-09 10:00	(1,740)	06-03 00:00	5,549	05-04 18:00	6,149
S25	04-27 13:00	22,249	04-26 21:00	19,381	09-09 10:00	(2,197)	04-18 01:00	5,008	04-16 09:00	4,611
S26	04-27 15:00	22,645	04-28 01:00	19,223	09-09 10:00	(1,912)	04-18 01:00	4,993	04-16 09:00	4,609
S27	04-27 15:00	22,902	04-28 01:00	19,566	09-09 10:00	(1,740)	06-03 00:00	5,541	05-04 18:00	6,149

6.12 SUMMARY

The single highest gross and net peak events occur in the month of April.

The idea of the solar sponge was also recently introduced by the Ministry of Power (MoP) in its amendment to the Electricity (Rights of Consumers) Rules. It directs the State Regulatory Commission to introduce a tariff rebate of 20% for Commercial and Industrial consumers having maximum demand more than ten Kilowatt (MoP 2023). As per MoP this shall be made effective from a date not later than 1st April 2024. The same amendment also suggests that for all consumers, except agricultural consumers, the Time-of-Day tariff shall be introduced. The ToU simulation in this chapter indicates that for the particular load profile of Tamil Nadu the introduction of solar sponge may result in

i. an increase in the peak instances on the gross load,
ii. a reduction in the peak instances on the net load,
iii. a significant reduction in the valleys/negative load instances on the net load (e.g., a reduction in the need for curtailment of renewables),
iv. an increase in ramping up instances greater than 2,500 MW/h and
v. an increase in ramping down instances greater than 2,500 MW/h.

Introducing a peak hour tariff increase of 40% surprisingly resulted in an increase in gross and net load peak instances and also increased the ramping down instances in the 3,500 MW/h regardless of the time slots chosen for peak hours. A peak hour tariff increase of 25% consistently showed better result when compared to the 40% tariff increase. The off-peak rebates of 0%, 5% and 10% did not result in noticeable impacts on the simulation results.

The ToU scenarios S5, S14 and S23 share the common variables of (i) +25% increase in tariff during peak hours, and (ii) a 5% tariff rebate during off peak hours. While they differ in either the time slots allocated for peak and off-peak hour tariffs or the addition of the solar sponge. These three scenarios will be taken for a deep dive analysis looking at seasonal variations in the next chapter.

07

In-Depth Analysis of Selected Time-of-Use Tariff Scenarios

From the 27 Time of Use (ToU) tariff scenarios, 4 specific scenarios have been thoughtfully selected for a comprehensive and detailed analysis. These distinct ToU tariff scenarios encompass S1, representing the absence of any ToU tariff framework. Additionally, the other scenarios, namely S5, S14, and S23, have a 25% increase in peak hour tariffs compared to standard rates, along with off-peak hour tariff rebate of 5%. Furthermore, the peak hours are defined as 6:00h to 10:00h and 18:00h to 22:00h for S5, and 5:00h to 7:00h and 17:00h to 23:00h for S14. S23 has similar peak hours as S14 along with an addition of a 20% solar sponge rebate spanning from 10:00h to 16:00h.

Table 10: Selected ToU Scenarios

Scenario	Peak tariff increase	Off-peak tariff rebate	Peak hours	Off-peak hours	Solar Sponge
S1	0%	0%	N/A	N/A	No
S5	25%	5%	6:00h to 10:00h 18:00h to 22:00hh	0:00h to 5:00h	No
S14	25%	5%	5:00h to 7:00h 17:00h to 23:00h	0:00h to 5:00h	No
S23	25%	5%	5:00h to 7:00h 17:00h to 23:00h	0:00h to 5:00h	10:00h to 16:00h tariff reduction of 20%

While the previous section compared 27 ToU tariff designs across key parameters, this chapter introduces a monthly and quarterly analysis dimension. Specifically, the focus is shifted towards evaluating the effects of the implemented ToU tariff scenarios in comparison to the baseline S1 scenario, characterised by the absence of ToU tariffs. Particular emphasis is placed on analysing the potential for load redistribution towards solar energy generation hours, aiming to enhance the integration of a higher share of renewable energy. In the following set of analyses, S1 (no ToU) is compared with the ToU tariff scenarios S5, S14, S23. Of which, there is a specific attention given to the S23 which has a solar rebate hour ('solar sponge') during the generation as mentioned above.

Table 6: Quarterly share of annual solar and wind energy generation

7.1 COMPARISON OF HOURLY AVERAGED ANNUAL GROSS LOAD DATA

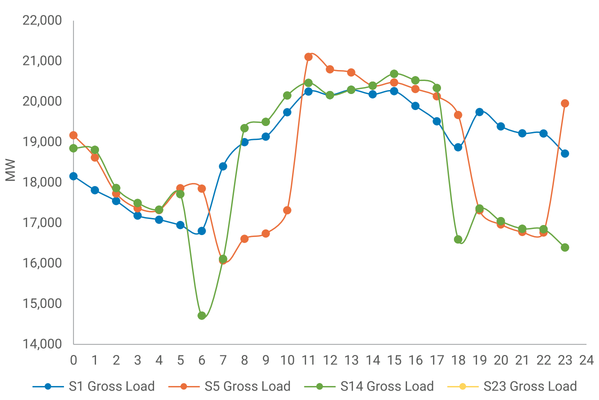
34% of the total daily energy demand of S23 occurs during solar hours between 10:00h and 16:00h. This share is 31% for S1.

The single highest peak gross load instance in S1, the baseline scenario, occurred at 13:00h on the 27th of April. Comparing the gross load curves for the selected ToU tariff scenarios on this day it is found that the peaks of the other scenarios surpass the peak gross load of Scenario 1 at 13:00h. Notably, S23, which offers rebates for consumption during the peak solar energy generation hours from 10:00h to 16:00h (as depicted in Figurre 28: Left), exhibits a substantially higher peak in gross load during these hours compared to the other scenarios.

Comparing the yearly average gross load profile, the contrast in the gross load between S1 and the remaining ToU tariff scenarios becomes more evident (Figure 28: Right). Compared to S1, the gross load profiles of the other ToU tariff scenarios exhibit higher load during the day-time hours, this is particularly pronounced for S23. This maybe contributed to the following factors: (i) the termination of peak hours at 10:00h, resulting in an increase in demand for S5; (ii) the rebate periods specific to S14; and the solar sponge rebates inherent to S23, nudging load to shift to solar energy generation hours.

Understanding how the peak shifts is an important parameter to measure the impact of a ToU tariff design. When it comes to the timing of the peak hours, S1(no ToU tariff) exhibits distinct morning and evening peaks at 8:00h and 20:00h respectively in the gross load. In contrast, the gross load of the other scenarios peak at 11:00h in the morning. Also, the other scenarios have a diminished morning peak and evening peak in comparison to S1, additionally, the time at which the evening peaks occur shifted from 20:00h to different hours for different cases. This is a noticeable shift in load distribution from peak hours to other time periods, especially in the solar hours of the day. To quantify this better, the average total load for a day and the average load during the solar hours are calculated and tabulated in Table 11. S23 registers 34% of the day's total load during the solar hours from 10:00h to 16:00h.

Figure 28: Left: Comparison of the hourly gross load data of Scenarios 1, 5, 14, and 23 on the 27th of 2024, when Scenario 1 reaches its highest demand of the year. Right: Yearly average hourly gross load data for Scenarios 1,5, 14, and 23.



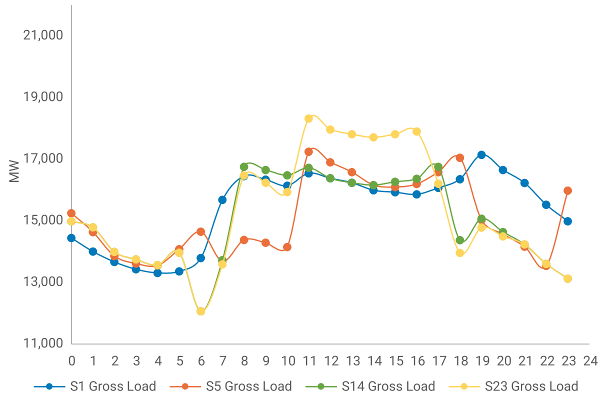


Table 11: Comparison of the energy of various scenarios and the percentage of energy falling under the solar hours of 10:00 to 16:00

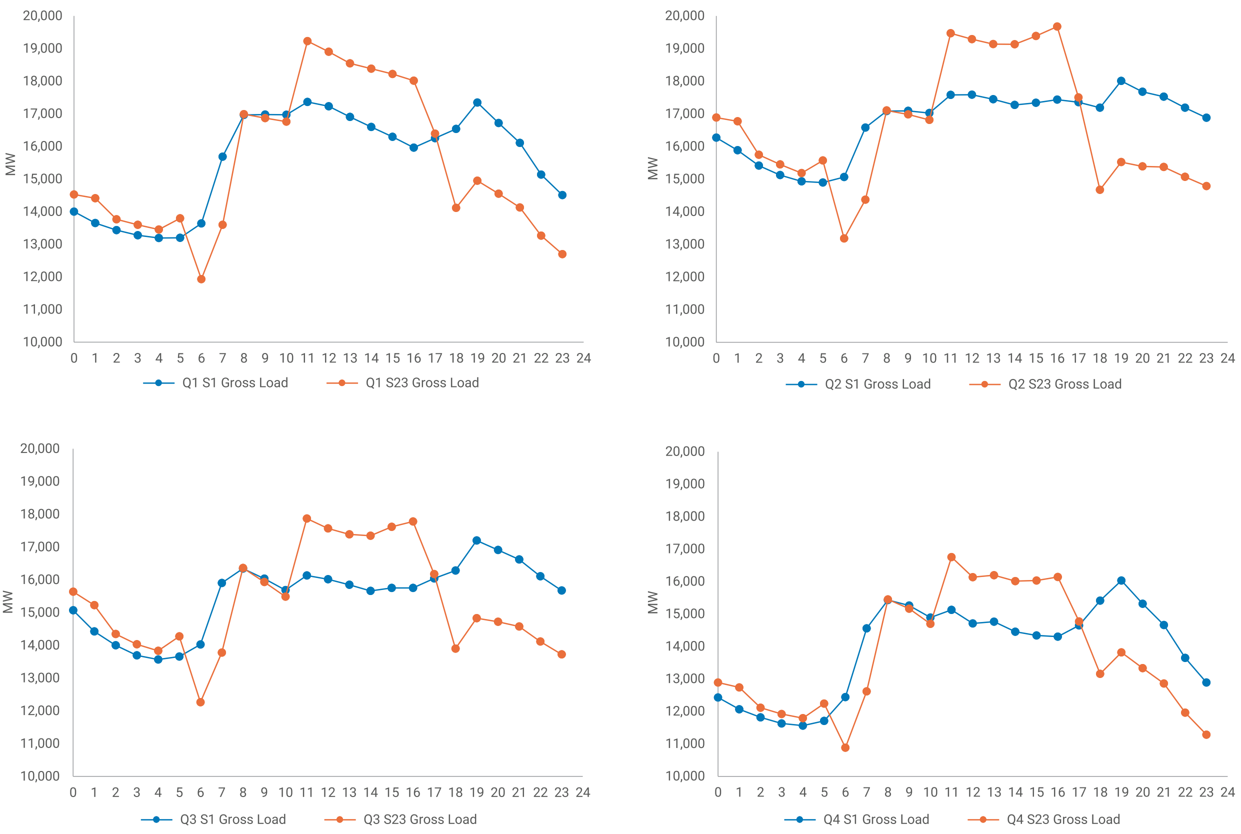
	S1	S5	S14	S23
Total energy consumed on an average day (MU)	370.50	362.23	360.62	367.24
Energy consumed between 10:00 to 16:00 (MU)	113.08	113.33	114.61	123.45
Energy consumed between 10:00 to 16:00 (%)	31%	31%	32%	34%

7.2 COMPARISON OF HOURLY AVERAGED QUARTERLY GROSS LOAD DATA

Compared to S1, S23 shows a rise in the morning gross load and a decrease in the evening gross load.

The hourly average gross load curve comparing S1 and S23 for all the quarters of a year is drawn in Figure 30. While S1 lacks any solar hour incentives, S23 provides incentives to consumers to shift loads towards for solar energy generation hours ('solar sponge'). The impact of the solar sponge is clearly visible through the higher daytime demand from 10:00h to 16:00h under S23 if compared to S1.This trend is observed throughout all the quarters, the load shifts towards the solar hours from the latter part of the day. This pattern becomes clear when we observe the significant load concentration in S23 between 11:00h and 16:00h and a difference between S1 and S23 from 17:00h to 23:00. This translates to a rise in morning load within the context of S23 as compared to S1 and a decrease in evening load for S23 in contrast to S1.

Figure 29: Comparison of gross load of S1 and S23 across the four quarters of a year



7.3 DISTRIBUTION OF THE TOP PEAK GROSS LOADS

The gross load peaks are concentrated in the April morning hours irrespective of the ToU tariff scenario.

Table 12 below displays the top five gross load instances by ToU tariff scenario. With the exception of S5 all 5 top gross load instances for each scenario occur in April. For S5 one instance was recorded in the month of March and four instances are recorded in April.

Table 12: Yearly distribution of the top five gross load peaks (number of occurrences)

	S1	S5	S14	S23
March	0	1	0	0
April	5	4	5	5

Further exploring the peak occurrences, the hourly distribution of the top five peaks throughout the year is plotted. Notably, all these peaks occur at 11:00h as shown in Table 13. That is, the gross load peaks tend to be concentrated on the morning hours irrespective of the scenarios and the quarters in a year.

Table 13: Hourly distribution of the top five peak across the year

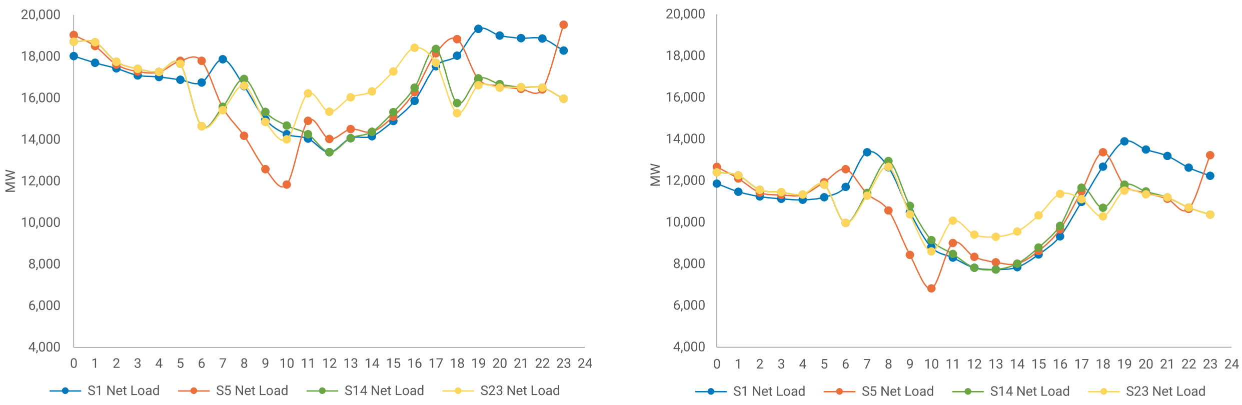
Hours>	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S1	0	0	0	0	0	0	0	0	0	0	0	2	0	1	1	1	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	0	0	0	0	0	0	0	0
S14	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	1	1	0	0	0	0	0	0
S23	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	1	1	0	0	0	0	0	0	0

7.4 COMPARISON OF HOURLY AVERAGED ANNUAL NET LOAD

Well-designed ToU tariffs reduce morning and evening peak loads.

The net load for all scenarios on April 27th (the day of S1's peak) and the hourly average net load for the year are compared. Notably, the evening net load of S1 is higher and the daytime load is lower if compared to the other ToU tariff scenarios. S5 depicts the highest load variations with a deep valley in the morning at 10:00h and a late-night peak at 23:00h. This high load variations are mitigated in S14 and S23 through redefinition of the peak and off peak hour time slots. The 'solar sponge' introduced for S23 is clearly visible with the increase in load from 10:00h to 16:00h (refer to Figure 30).

Figure 30: Left: Comparison of the hourly net load data of Scenarios 1, 5, 14, and 23 on the 27th April of 2024, when Scenario 1 reaches its highest demand of the year. Right: Yearly average hourly net load data for Scenarios 1,5, 14, and 23



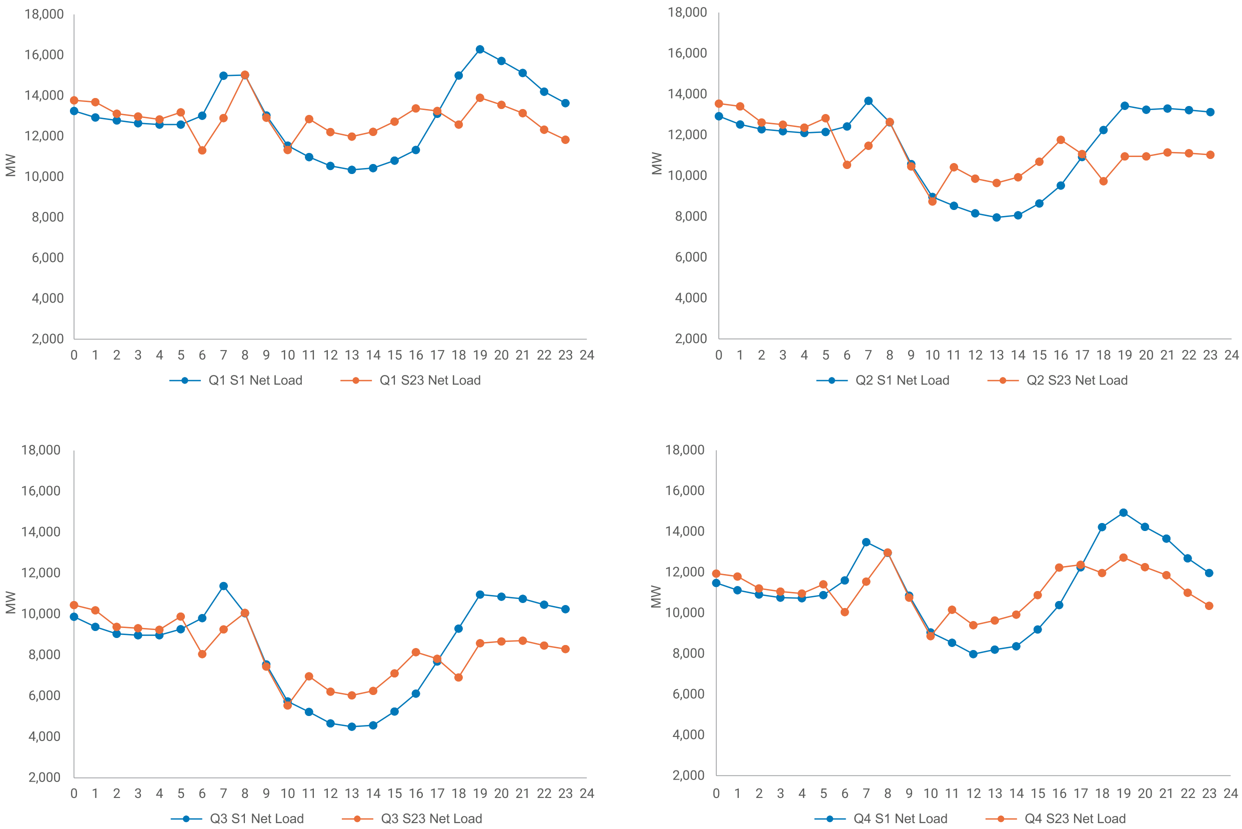
7.5 COMPARISON OF HOURLY AVERAGED QUARTERLY NET LOAD

The load during the early hours of the day shifts to solar hours due to the solar sponge rebates.

The hourly net load curves are divided into four quarters of the year. It is observed that Q3 where the solar and wind generation are more, has the lowest net load among all the quarters. S1 experiences net load peaks both in the morning and evening at 7:00h and 19:00h, respectively.

In terms of the morning peak, the load during the early hours in S23 shifts to solar hours, leading to a reduced peak in that period. However, this shift results in a peak at 8:00h due to the conclusion of the peak hour tariff slot of this S23 at 7:00h. Consequently, some loads of S23 from the morning peak from, 5:00h and 7:00h shift to 8:00h. All of S1 evening peak occur at 19:00h. With the exception of quarter 2 all of S23's net load peak equally occur at 19:00h, but the decreases in magnitude compared to S1 is significant (refer to Figure 31).

Figure 31: Comparison of net load of S1 and S23 across the four quarters of a year

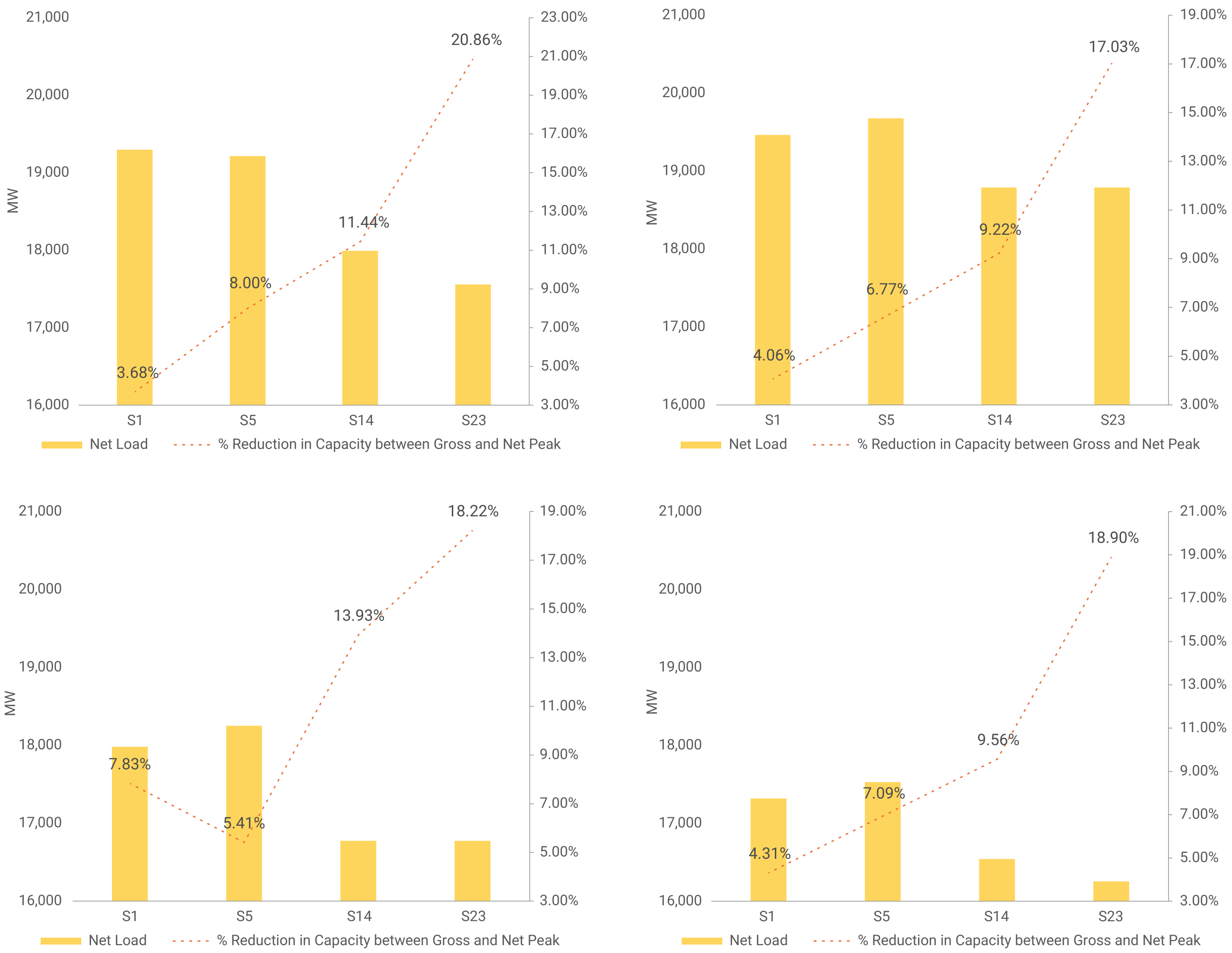


7.6 COMPARISON OF GROSS AND NET LOAD

S23 has gross load peak to net load peak difference across all quarters.

Regarding the reduction of gross load to net load, a comparison is made between each scenario's net load and its efficacy in achieving this reduction across quarters. S5, operating with ToU peak hours from 6:00h to 10:00h and 18:00h to 22:00hh, exhibits a slight improvement in reducing gross load to net load compared to S1 (no ToU implementation) across all quarters except quarter 3. Meanwhile, S14, with peak hours shifted to 5:00h to 7:00h and 17:00h to 23:00, outperforms both S1 and S5 in gross load reduction. On the other hand, S23, sharing the same peak hour timings as S14 but featuring a solar hours rebate, achieves the most significant reduction in gross load to net load as shown in Figure 33. This is a clear attribution to the 'solar sponge' hours as mentioned in the earlier part of this chapter. This analysis underscores the advantages of implementing ToU tariffs compared to not having them, as ToU tariffs can help shift or flatten the load curve to a certain degree. However, strategically altering peak hours can yield even better improvements. Lastly, combining peak hours, rebate hours, and incentives for solar hour consumption, the 'solar sponge', effectively redirects demand to solar hours from other times, eventually reducing peak load during those periods.

Figure 32: Comparison of net load and the percentage reduction in capacity between gross and net load peak



7.7 DISTRIBUTION OF THE TOP PEAK NET LOADS

All the top peaks of the net load occur in the month of April.

The occurrences of the top 5 net load instances within a year are examined for each of the selected ToU tariff scenarios. Similar to the highest five peak gross load occurrences discussed earlier, the peak net load instances also predominantly appear in the month of April, with only one instance occurring in March for S1.

It is found that four out of the five top net peaks of S1 occur at 19:00h while four out of the five top net peaks of S5 occur at 23:00h and the top net peaks of S14 and S23 occur during the late night hours of 0:00h and 1:00h. In contrast to the overall trend of the gross load where the top five peak instances where found between 11:00h and 17:00h, the peaks of the net load occur either in the between 18:00h and 01:00h. Solar energy has helped in the reduction of the gross load peaks that would otherwise occur in the middle of the day.

Table 14: Yearly distribution of the top five net load peaks (number of occurrences)

	S1	S5	S14	S23
March	1	0	0	0
April	4	5	5	5

Table 15: Hourly distribution of the top five peak net loads across the year

Hours>	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	1	0	0
S5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	4
S14	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S23	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

7.8 NET LOAD FREQUENCY DISTRIBUTION

S23 shows a lower net load instance in the upper ranges as well as the lower ranges.

Upper ranges of the net load: Notably, S1 exhibits a higher frequency of net load occurrences in the upper load ranges, specifically within the span of 14,000 MW to 20,000 MW. Conversely, S5, S14, and S23 display lower load instances in these upper load ranges, as shown in Figure 34: Left and Figure 33 This observation underscores the alignment of demand with renewable energy generation, resulting in reduced occurrences of load within the higher load ranges for S5, S14, and S23.

Lower ranges of the net load: Within the lower load ranges spanning from 0 MW to -4,000 MW, S23 demonstrates to be effectively decreasing instances up to -2,000 MW and preventing them from exceeding this threshold in contrast to the other scenarios as shown in Figure 34: Right. This could be attributed to shifting the load towards the time periods having a higher count negative load instances, eventually reducing the instances of negative load in general., which potentially avoids curtailment.

Figure 33: Net Load frequency distribution for scenarios S1, S5, S14, and S23

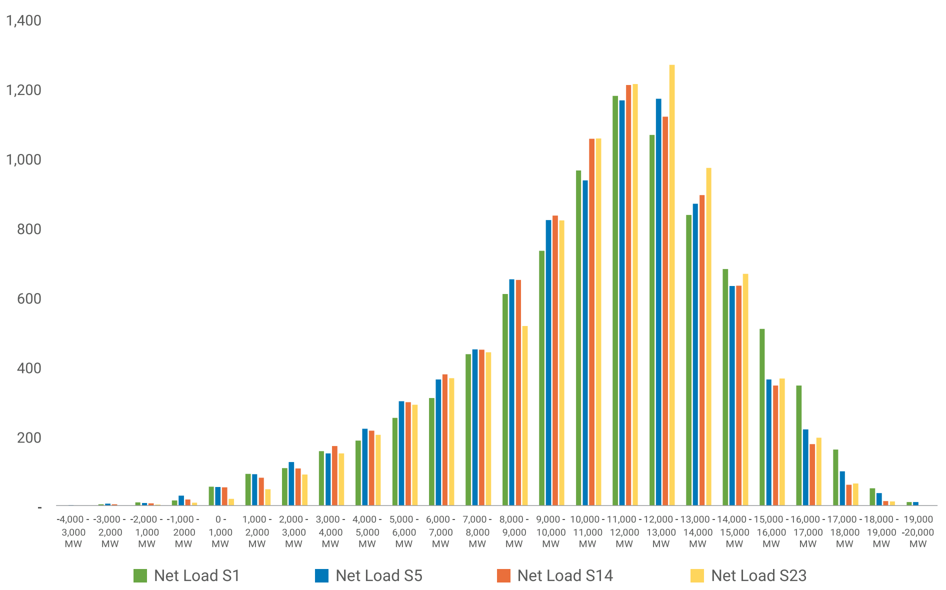
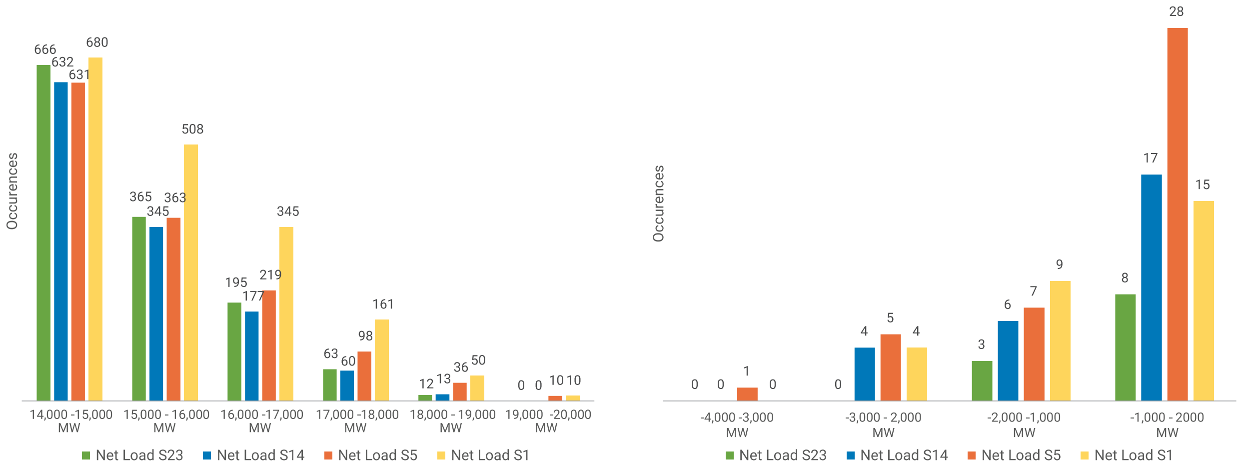


Figure 34: Left: Net Load frequency distribution for scenarios S1, S5, S14, and S23 for the range 14,000 MW to 20,000 MW Right: Net Load frequency distribution for scenarios S1, S5, S14, and S23 for the range -4,0000 MW to -0 MW



7.9 YEARLY RAMPING INSTANCES ON NET LOAD

S23 has the least ramping up instances and the most ramping down instances among the ToU implemented scenarios.

Among the selected scenarios, S1 (without ToU tariff) exhibits the fewest net load ramping up instances exceeding 2,500 MW/h. S23 demonstrates the lowest occurrences of ramping up at 2,500 MW/h among the ToU-implemented scenarios. This shows that the introduction of ToU and aligning the demand with renewable generation decreases the ramp up instances, but leads to increased ramping down instances.

Table 16: Instances of ramping on the net load of scenarios 1, 5,14, and 23.

	Ramping up > 2,500 MW/h	Ramping down >2,500 MW/h
S1	95	123
S5	372	111
S14	161	159
S23	121	192

7.10 QUARTERLY RAMPING INSTANCES ON THE NET LOAD

S23 exhibits fewer instances of ramping up above 2,500 MW/h.

Upon analysing the instances of both ramping up and ramping down on the net load for the scenarios, it becomes evident that the scenario without ToU tariff implementation exhibits fewer instances compared to the other scenarios in all the quarters. Upon examining the scenarios for which ToU tariff is implemented, namely S5, S14, and S23, it becomes apparent that S23 exhibits fewer instances of ramping up above 2,500 MW/h compared to S5 and S14. Conversely, S23 shows a higher number of instances of ramping down greater than 2,500 MW/h across all the quarters if compared to S5 and S14.

Table 17: Instances of ramping up on the net load of scenarios 1, 5,14, and 23 for all the quarters

	Q1				Q2				Q3				Q4			
Scenarios	S1	S5	S14	S23	S1	S5	S14	S23	S1	S5	S14	S23	S1	S5	S14	S23
Ramp up >2,500 MW/h	19	87	50	29	16	127	48	55	20	83	26	20	40	75	37	17
Ramp down > 2,500 MW/h	26	24	28	35	31	34	65	73	33	20	33	38	33	33	33	46

7.11 HOURLY INSTANCES OF RAMPING ON THE NET LOAD

S23 exhibits ramping up at midnight at 8:00h whereas S1 has ramping up at the evening hours of 17:00h and 18:00h coinciding with the evening peak.

S23, has the ramping up instances concentrated at 0:00h and 8:00h. The midnight ramping up could be due to the fact that loads are shifted from the peak hour time slot (17:00h to 23:00h) to the late night hours. Similarly, the need for ramping up at 8:00h could be due to the end of the peak hours tariffs time slot at 7:00h, resulting in an increased demand at 8:00h leading to a ramping up (refer to Table 19). When it comes to ramping down, S23 exhibits a ramping down at 6:00h and 9:00h. The ramping down patterns of S1 and S23 align, yet S1's ramping up needs during evening peak hours could potentially strain the grid in fulfilling the demand. In contrast, S23 effectively mitigates these challenges (refer to Table 20).

Table 18: Ramping up instances on the net load greater than 2,500 MW/h by hours of occurrences

Hours>	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S1	0	3	0	0	0	0	0	24	0	0	0	0	0	1	0	0	2	24	30	11	0	0	0	0
S5	0	3	0	0	0	0	0	0	0	0	0	84	0	1	0	0	6	44	53	0	0	0	0	181
S14	51	4	0	0	0	0	0	3	47	0	0	0	0	1	0	0	6	45	0	4	0	0	0	0
S23	51	4	0	0	0	0	0	2	32	0	0	17	0	1	0	0	8	0	0	6	0	0	0	0

Table 19: Ramping down instances on the net load greater than 2,500 MW/h by hours of occurrences

Hours>	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S1	0	1	0	0	0	0	0	0	6	93	21	1	0	0	0	0	0	0	0	0	0	0	1	0
S5	1	3	0	0	0	0	0	10	1	64	8	0	1	0	0	0	0	0	0	23	0	0	0	0
S14	0	1	0	0	0	0	38	0	0	91	20	1	1	0	0	0	0	0	7	0	0	0	0	0
S23	0	1	0	0	0	0	38	0	0	114	27	0	1	0	0	0	0	6	5	0	0	0	0	0

Of all the cases examined, such as S1, S5, S14, and S23, S23, which has a solar hour rebate between 10:00h to 16:00h, shows positive results. S23 concentrates 34% of its average daily demand during the solar hours from 10:00h to 16:00h. Also, S23 has a decreased evening peak load in comparison to other scenarios, especially to S1. Furthermore, S23 exhibits fewer instances of load in both upper and lower net load ranges, successfully mitigating both peaks and valleys through optimal utilisation of solar generation in alignment with demand. This facilitated the grid integration of higher solar energy shares, and if sourced from distributed solar energy systems can also result in transmission, distribution and generation capacity savings.

When it comes to net load ramping requirements, the scenarios for which the Time of Use (ToU) is implemented such as S5, S14, and S23 have increased instances of the net load ramping up and ramping down greater of 2,500 MW/h in comparison to the S1. However, within the ToU implemented scenarios, S23 has reduced instances of ramping up but an increased instance of ramping down which could be attributed to the load concentrating on the solar hours requiring a ramp down for the reduction of the load.

08
Case Studies

The following global case studies highlight practical examples on how demand side interventions including ToU tariffs and demand response programs can improve cost efficiency of grid operation and facilitate the integration of a higher renewable energy share.

8.1 SOLAR SPONGE RATES - AUSTRALIA

Australia currently has approximately three million households with solar rooftops, and this number is expected to double to six million within the next decade (AEMC 2021). Notably, the state of South Australia stands out with its high penetration of renewable energy. At certain times of the year, the state's electricity demand is fully met by solar and wind power sources. This shows how well-positioned the South Australian electricity grid is, which is predominantly powered by solar and wind, and supported by energy storage systems (IEEFA 2021). In line with this progress, the South Australian government has set an ambitious target of achieving 100% net renewables by 2030, aiming to accomplish this goal even earlier. Therefore, the uptake of solar energy and other Distributed Energy Resources (DER) is going to increase in the years to come. The increase in solar energy will also mean an increase in rooftop solar and an increase in prosumers. A prosumer retrieves both energies from the grid and self-produced energy from rooftop solar panels or other generating devices while injecting into the grid the power over the need (Smart Meters 2020). In the traditional one-way grid, the electricity generated only travels from the point of generation to the point of consumption. But with the increase in prosumers, electricity is also generated at the consumer's end. This results in technical challenges for the grid such as the two-way flow of electricity, a change in the usage of electricity, and a change in the pattern of the peak (AEMC 2021). A 'Solar Sponge' network tariff was introduced on 1st July 2020, in which from 10 AM to 3 PM, electricity charges are 75% discounted from 18 c/kWh to 3.6 c/kWh (IEEFA 2021). This encourages energy use during the day hours when solar generation peaks. Apart from this, the state offers subsidies for residential battery storage (REN 21 2022).

8.2 DEMAND RESPONSE AND TIME OF USE TARIFFS IN VARIOUS COUNTRIES

A Time of Use (ToU) tariff has time-varying price signals based on power system balance or market prices. In a ToU scheme, customers can adjust their electricity consumption to reduce their expenses (IRENA 2019). Economy 7 is a ToU tariff scheme that was introduced in the UK to help consumers save money on their electricity bills. Under this scheme, customers are offered lower electricity rates during a 7-hour off-peak period, when energy prices and demand are typically at their lowest. According to a survey of 3,000 electricity consumers in the UK, there is interest in the time of use (ToU) tariffs. It was also discovered that ToU tariffs can reduce peak demand by 5 to 10% (Citisensadvice 2020) and (Energy savings Trust of UK 2020). As per (IRENA 2019), in a similar ToU tariff programme conducted in Sweden, the peak hours contributed to 23% of the total electricity usage which was reduced to 19% upon the implementation of the program.

According to the American Council for an Energy-Efficient Economy (ACEEE), in the U.S. in 2015, about 200 TWh of electricity, or more than 5% of retail sales, were saved due to demand response programmes. This also substantially reduced peak demand. On a median basis, for each 1% reduction in electric sales for a utility, peak demand reductions from demand response programmes are 0.66% of peak demand for the utility. If these trends hold for future years, it means that for a utility that reduces retail sales by 15%, peak demand savings will be around 10% (ACEEE, 2017).

The French Tempo tariff – a critical peak pricing tariff launched in the 1990s – has reduced the national peak load by about 4%, with households shifting about 6 GW of load daily (Rosenow et al., 2016).
In 2012, TATA Power Company in Mumbai initiated a pilot program involving the participation of consumers, airports, commercial entities, and IT parks. During this program, participants collectively switched off their air conditioning units, chillers, generators, and other electrical devices for a period of two hours. As a result of their efforts, the overall electricity load was reduced by 15 MW, showcasing the potential impact of demand response initiatives (AEEE 2022).

Similarly, in 2021, a demand response program was conducted in Delhi, specifically targeting residential consumers. As part of this program, consumers were incentivized with rebates to either shed or shift their electricity usage to other hours. The program successfully resulted in a shedding of 480 MW across 16 demand response events, highlighting the significant contribution residential consumers can make to manage electricity demand during peak periods (AEEE 2022).

8.3 IMPACT OF ELECTRIC VEHICLES ON THE TIME OF USE TARIFFS – CALIFORNIA, USA

The market for electric vehicles has consistently grown in the state of California, USA. In the year 2020, the sales of EVs contributed to 9% of the overall sales of vehicles (iScience 2022). The addition of EVs in the state poses a challenge as well as brings an opportunity from a power grid's perspective. The challenge is the increase in demand, while the opportunity is the utilisation of renewable energy during its peak generation by EVs. If the EV charging is managed properly at a certain period, then it could prove to be useful to control the load thereby becoming not only a good grid resource but also resulting in a reduction in the bills for the customers. In California, a real-life study called Change Forward 2.0 on the integration of EVs into the grid was conducted. This study examined various ToU Scenarios such as avoiding EV charging on peak timings, shifting charging to locations away from home, increasing charging during renewable energy hours, and increasing the period of charging. A base case was first captured to understand the impacts of the various ToU Scenarios on the load (TCM 2021).

In one of the ToU Scenarios, the participants are allowed to charge their vehicles in their homes and are allowed to optimise their charging based on the following:

1) Optimisation with the Transactive Energy signal price: The transactive energy signal price coincides well with the peak pricing. The vehicles are optimised to have a lesser transactive energy signal. Vehicle charging schedules were optimised based on cost minimisation and user-provided information, such as desired departure times. Plug-in and target departure times were analysed, with plug-in times primarily occurring from 4:00 to 11:00 p.m. and departure times the next day from 5:00 to 9:00 a.m. Baseline charging assumed immediate charging after plug-in, while optimisation aimed to shift charging away from high-priced evening peak times to periods of low energy prices, typically in the early morning and midday. The comparison between optimised and baseline charging schedules showed the effectiveness of the optimisation algorithm in reducing costs and shifting load away from peak times. The analysis demonstrated a reduction in peak load and a decrease in energy costs related to EV charging.

2) Load decrease events: This focused on examining the potential of electric vehicles (EVs) participating in TCM (Transactive Control Mode) to act as a grid resource for load reduction. The goal was to evaluate the feasibility of EV fleets becoming a formal grid resource in day-ahead energy markets. This analysis examined the performance of load decrease events at the household level. Establishing a clear trend regarding the effectiveness of load-decrease events for participating EVs and the total household load proved to be challenging. The ability of EVs to actively engage in load decrease events determined by the baseline presented complexities, underscoring the intricacies of integrating EVs as a grid resource.

3) Load increase events: This explored the EV fleet as a demand resource for load increase. This type of event is beneficial when the grid requires additional load, such as during periods of surplus supply from increased renewable energy generation. Overall, the performance in load increase events was better than load decrease events. A notable finding was that vehicle demand at home exhibited greater elasticity during load increase scenarios compared to load decrease scenarios. The system demonstrated its ability to function as a grid resource by shifting load to more advantageous times for the grid and lowering customer energy costs. The system also proved its versatility by operating effectively in both demand increase and decrease scenarios, benefiting both the grid and the customers. As the market share of EVs continues to grow, optimising their charging and utilising them as grid resources will become increasingly valuable. As a result of experimenting with this case, the charging is shifted out of the evening hours to the early morning hours. This resulted in cost savings for the vehicles that participated in this program for a period of 13.5 weeks. Similarly, there were different cases experimented with the drivers of EVs which resulted in direct cost savings on utility costs during the period of the experiments on all the participating vehicles combined.

09
Conclusion

In conclusion, the findings highlight important considerations regarding incorporating wind and solar energy into Tamil Nadu's energy mix. As per the RPO mandate (MoP 2022) a total of 29.91% of grid electricity by 2024 needs to come from renewable energy sources. Three different renewable energy scenarios were simulated, varying in their respective share of wind and solar energy. These three renewable energy scenarios were evaluated based on key grid management parameters: net load peak instances, net load valleys and instances of negative loads, and the need for ramping up and ramping down. The RE scenario 3 that had a relatively higher share of wind energy (17.36% of wind and 11.47% solar) showed the lowest instances of ramping up and ramping down, while it had similar results for the net load peak and net load valley instances compared to the scenario where wind and solar had an equal share. Therefore, the RE scenario 3 was selected for the consecutive simulations.

The analysis identifies specific time periods when solar and wind generation reaches their peaks. Solar consistently reaches its peak at 13:00h across all quarters, while wind peaks at 17:00h during the second and third quarters of the year. This information can be valuable for grid operators and energy planners in optimising the utilisation of these renewable resources. Furthermore, the positive impact of solar and wind energy is reducing the frequency of high-net load occurrences, suggesting the effectiveness of solar and wind in mitigating high-demand situations. However, integrating solar and wind energy into the system increases the demand for grid flexibility services, on the generation and on the demand side. Adequate ramping capacity is crucial for ensuring a reliable and stable energy supply. With the projected higher share of wind and solar energy the instances of renewable energy curtailment are expected to increase. Currently there is a lack of policy or technology mechanism to deal with surplus renewable energy, curtailed solar and wind energy is not being compensated for and the existing energy storage capacity in Tamil Nadu of 500 MW pumped storage hydropower (PSH) is insufficient to deal with a higher share of renewables. While the recent RPO notification by the Ministry of Power (MoP 2022) also introduced a mandate for energy storage (energy storage RPO) of 1.50% of total energy in FY 2023-24 and 2.00% of total energy in FY 2024-25 a dedicated evaluation by the grid operator to assess the adequate energy storage capacity need and the compensation of generators for curtailed renewable energy is required. Overall, these findings provide insights into the extent ToU tariffs can facilitate the grid integration of solar and wind energy.

Tamil Nadu's gross load profile generally peaks in the late morning and in evening. The simulated ToU tariff scenarios with a change in the peak and off-peak hour time slots and a peak hour tariff increase show an increase in gross peak load instances on the same hours. This is a positive sign as the load accumulates during the solar generation hours. The expected reduction of peak load instances of these scenarios is significant as this can add to the grid integration of a higher share of solar energy and may also reduce the overall power purchase cost. Also, the existing peak time slots of 6:00h to 10:00h and 18:00h to 22:00h result in increased instances of negative net load and of instances in the lower net load ranges. This does not aid the integration of solar and wind. When the peak time slots are changed from 6:00h -10:00h and 18:00h - 22:00h to 5:00h - 7:00h and 17:00h -11:00h, the instances in the lower ranges of the load decrease leading to a better use of the available renewable energy. When it comes to ramping requirements, both ramping up and down, scenarios with a higher peak hour tariff of 40% show a higher ramping requirement. The peak hour tariff with 25% shows more favourable results.

Table 20 Summary of results

	Peak - Gross Load (MW)	Peak - Net Load (MW)	Lowest Valley - Net Load (MW)	Peak Ramping Up Net Load (MW/h)	Peak Ramping Down Net Load (MW/h)
S1	20,288	19,464	-2,755	4,108	4,506
S5	21,104	19,676	-3,401	4,906	4,506
S14	20,696	18,788	-2,609	4,542	4,489
S23	22,645	18,788	-1,912	4,542	4,623

Overall, these findings underscore the potential benefits of implementing ToU tariffs for all consumer categories, including reduced peak loads, load range occurrences, and ramping requirements. Careful consideration of peak hour tariffs and adjustments to peak hours can further optimise load distribution and maximise the efficiency of the power grid.

To meet its RPO and its climate change objectives Tamil Nadu will have to accelerate the deployment of renewable energy generation. In order to manage the variable nature of wind and solar energy generation and of demand the grid management will require a higher degree of demand and generation flexibility services. An evaluation and implementation plan of such grid flexibility services may be undertaken by the grid operator. Some recommendations to unlock a higher degree of grid flexibility for integration of a higher renewable energy share are listed below:

Table 21 List of recommendations

Recommendation	Agency
(i) Gradually apply ToU tariffs to all electricity consumer categories.	TNERC
(ii) Carefully evaluate the time slots assigned to peak and off-peak hours and ensure they meet the defined grid management objectives.	TNERC
(iii) Introduce a solar sponge (e.g., a tariff rebate during peak solar energy generation hours), to better facilitate the integration of a higher solar energy contribution.	TNERC
(iv) Introduce demand response programs for industries and specific consumer appliances such as electric vehicles, air conditioners and hot water heaters.	TANGEDCO
(v) Actively promote and facilitate distributed energy generation such as rooftop solar and battery energy storage systems.	TANGEDCO
(vi) Plan and deploy energy storage solutions to provide essential grid support services.	TANGEDCO
(vii) Introduce renewable energy curtailment compensation regulations to ensure continuous investment in the state's renewable energy sector.	TNERC

10
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11 Appendix

Methodology

This section outlines the approach that was used for modelling the impact of ToU tariffs on key parameters of grid operation and integration of renewable energy resources.

Data sourcing

Load data in hourly intervals is required for both the demand and for the solar energy and wind energy generation.

For this report, the load and generation data for the year 2022 was sourced from the State Load Dispatch Centre in Tamil Nadu (SLDC-TN).

Load forecasting

A percentage value for an average annual increase in electricity demand is utilized to estimate the total electricity demand for the year selected for the ToU tariff modelling exercise. The estimated total electricity demand is then distributed proportionally across each day maintaining the distribution observed in the baseline year.

For this report the load forecasting for 2024 was based solely on the load data from 2022 as a reference. An increase in energy demand of 7% was assumed. While the Central Electricity Authority (CEA 2022) assumed an average annual electricity demand increase of 5.59%. The higher estimated energy demand of 7% utilized in this report attempts to account for (i) resumption of industrial and commercial activities following the conclusion of the COVID-19 pandemic and (ii) possibly for a higher elective vehicle charging demand.

Modelling RE Scenarios

Three renewable energy scenarios are simulated. The scenarios are defined by the varying share of solar and wind energy. Hourly wind and solar energy generation profiles are generated considering varying solar and wind shares and utilizing the wind and solar generation data from the baseline year. The net load for each of the renewable energy scenarios is then computed.

The renewable energy purchase obligation (RPO) as suggested by the Ministry of Power (MoP 2022) has been utilized to define the total renewable energy share for the target year 2024. The RPO for 2024 was set at 28.83%.

Load analysis

A detailed analysis is conducted, with a focus on its distribution frequency within the top load intervals known as the load frequency distribution and is also analysed for the instances of ramping up and down.

Load frequency distribution: During analysis, distinct scenarios with unique load curves are considered. It's vital to establish a range that encompasses all these load curves to have consistent intervals throughout. Intervals are set in 1,000 MW increments, adjustable to incorporate every scenario's maximum and minimum loads. These intervals serve as the basis for plotting the load frequency distribution, enabling a thorough understanding of load distribution patterns.

Instances of ramping: To assess ramping requirements, three thresholds are employed: ramping up and down beyond 1,500 MW/hr, 2,500 MW/hr, and 3,500 MW/hr. Instances of ramping up and ramping down requirements for each of the 3 defined thresholds are counted. A significant count of these instances particularly in the higher ranges, signify high demand for ramping up and down of the generation fleets.

In this report, some or all the following parameters were used for evaluating the performance:

1. Gross load in top intervals
2. Net load in top intervals
3. Net load in lower intervals
4. Net load ramping up instances
5. Net load ramping down instances

Modelling of various ToU scenarios: The relationship between pricing and electricity consumption is crucial in understanding the impact of different ToU tariff structures. The price elasticity of demand refers to the proportional change in demand resulting from a proportional change in electricity prices. Mathematically this can be represented as:

$$\varepsilon = \frac{\Delta l / l_0}{\Delta c / c_0}$$

Where ε is the price elasticity, l_0 is the initial load, Δl is the change in load, c_0 is the initial cost, and Δc is the change in cost. The magnitude of price elasticity of electricity demand varies across regions, consumer categories, countries, and other economic factors as implied in Energy Economics (2021).

However, electricity consumption is not solely influenced by the cost in a specific hour but also by adjacent hours. When considering responses over multiple time periods, the price elasticity coefficient can be categorized into two parts: the self-elasticity coefficient and the cross-elasticity coefficient. From self-elasticity coefficient and cross-elasticity coefficient, the price elasticity matrix (PEM) is used for the interactive model between load demand and price.

Price Elasticity Matrix:
The price elasticity matrix used for the modelling is a 24×24 matrix for predicting 24-hour load under the ToU tariff, it consists of four key parameters:

i. Price Elasticity: This reflects the change in load in response to a change in price. A higher price elasticity indicates greater responsiveness of electricity demand to price fluctuations. Price elasticity can be divided into two elements:
   a. Self-Elasticity: This quantifies the change in load due to price changes within the same hour. Generally negative, it signifies that an increase in price leads to a decrease in demand within the same hour.
   b. Cross Elasticity: This measures the change in load demand in one hour due to price changes in other hours. It gauges the demand responsiveness between different time periods.

ii. Non-Responsive Hours: These are hours that remain unaffected by tariff changes, exerting no impact on demand either within the same hour or in other hours.

iii. Responsive Window: This defines the range of neighbouring hours within which changes in the tariff are reflected in demand.

iv. Lossy Factor: It quantifies the amount of load allocated to different hours while shifting.

The cross-elasticity coefficient depends on self-elasticity coefficient, non-responsive hours, responsive window, and the lossy factor.

Matrix Representation:
Consider the matrix with rows represented by ‘i’ ranging from 1 to 24 and columns represented by ‘j’ also ranging from 1 to 24. In this context:

$$\varepsilon_{ii} = \frac{\Delta l_i / l_i}{\Delta c_i / c_i}$$

$$\varepsilon_{ij} = \frac{\Delta l_i / l_i}{\Delta c_j / c_j}$$

ε_ii represents self-elasticity coefficient and ε_ij represents cross-elasticity coefficient.

However, in this study, two Price Elasticity Matrices (PEMs) were employed, namely PEM 1 and PEM 2, each characterized by distinct parameter sets outlined in Table 22.

Table 22: Parameters for PEM matrix

Parameters	PEM 1	PEM 2
Price elasticity	-0.75	-0.48
Responsive window	4	4
Non-responsive hour	None	1,2,3
Lossy factor	0.7	0.7

PEM 1 was applied to the Industrial and Commercial (C&I) consumer categories with a price elasticity value of -0.75 (Csereklyei, 2020) indicating higher sensitivity to price change when compared to all other categories with price elasticity of -0.48 (Pellini, 2021). It’s noteworthy that the C&I categories lack designated non-responsive hours, suggesting consistent activity, whereas PEM 2 has non-responsive hours as 1:00, 2:00, and 3:00 non-responsive hours assume that the consumer will not respond to any price signal during these time periods.

The baseline load profile utilized on the ToU scenario analysis will need to be a load profile that is not impacted by a ToU tariff. In the case where the existing load profile available is after the implementation of ToU tariffs, a baseline load profile with no ToU tariff will be reconstructed. Further, the load profile will be subdivided into responsive and non-responsive load. The responsive load is further segmented into sectors that may vary in regard to its responsiveness to ToU price signals.

The 2024 demand data was estimated utilizing the 2022 load data for Tamil Nadu. In 2022 a ToU tariff for HT industrial and commercial consumers was applicable. A load profile for 2024 was constructed that eliminated the expected impact of this 2022 ToU tariff, in order to arrive at a load profile with no ToU tariff, please refer Figure 35 for HT C&I load profile with and without ToU Tariffs.
Further all demand that is supplied by the distribution licensee in the state was defined as responsive load, whereas all load under the Open Access (OA) category has been defined as non-responsive load. The responsive load was further segmented into C&I load and ‘Other’ load.

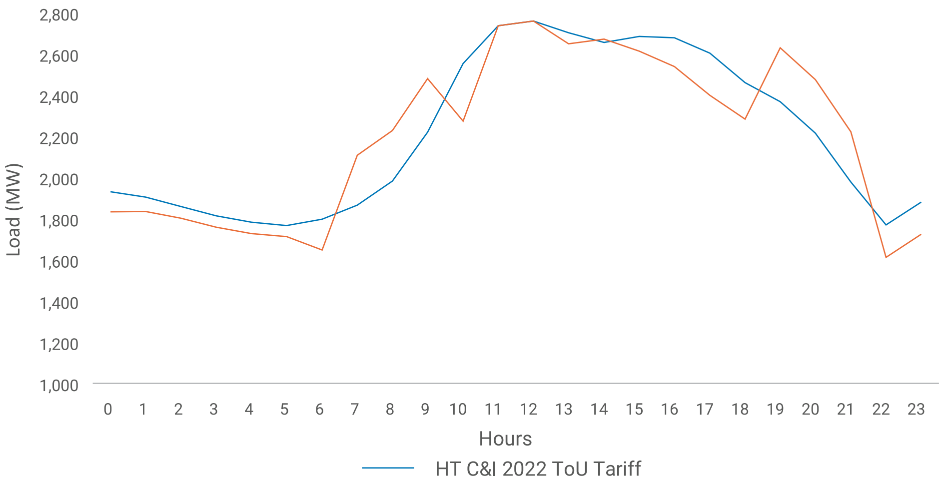
Reconstruction of load without ToU

After load distribution, the load on which the old ToU tariff is applied is subjected to a reverse ToU matrix incorporating complementary (negative) tariffs. This process yields the responsive load with no ToU

In the context of Tamil Nadu, the forecasted data represents the load profile with 2022 ToU tariff, ToU was exclusively applied to the High Tension (HT) Commercial and Industrial (C&I) categories. The normalised commercial and industrial load under the 2022 ToU framework provides proportion for the distribution of HT Commercial and HT Industrial load on hourly basis.

Note: The reverse ToU matrix is identical to the PEM matrix; except, the lossy factor used here is the inverse of the lossy factor used for PEM. Complementary tariff entails changing peak hours from old ToU tariff to off-peak, by changing higher tariff with rebate, and vice versa.

Figure 35: HT C&I hourly average load profile with ToU tariff design of 2022 and reconstructed load profile without ToU tariff



Segmentation of load profile into responsiveness groups

The data from State Load Dispatch Centre (SLDC) encompasses both utility generation and OA contributions However, ToU regulations do not apply to OA.

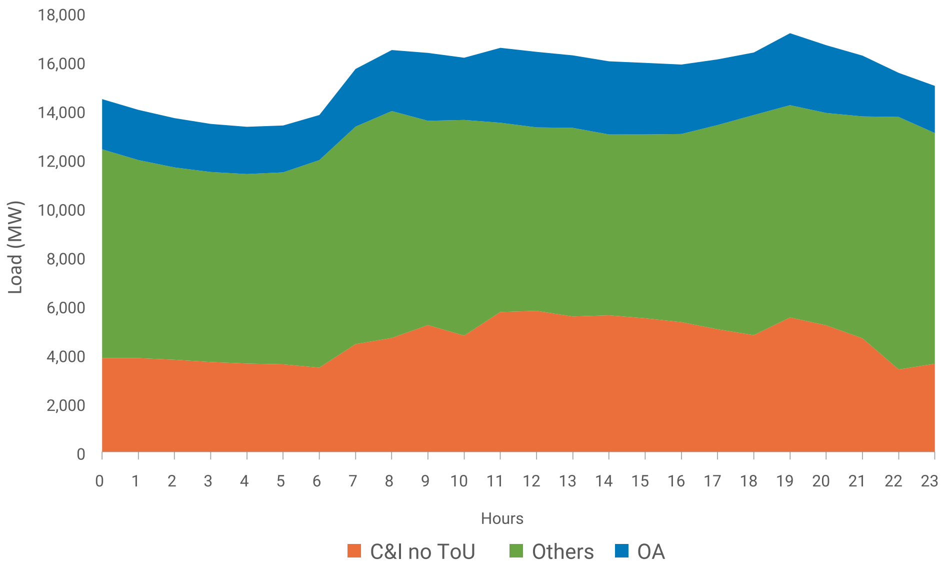
The forecasted data was categorized into two components:

1. **Non-responsive load:** This load segment does not responsd to any ToU price signals and remains unaltered. In case of Tamil Nadu, OA serves as non-responsive load. To derive a load profile for the OA demand we normalized and combined load profile for commercial and industrial consumers.

2. **Responsive load:** ToU principles are enforced on this segment of the state load, The responsive load is derived as a difference between hourly load of the state minus the hourly total non-responsive load.

The responsive-load was further subdivided into Commercial and Industrial load (this includes both LT and HT C&I loads) and "Other Load' (representing responsive load minus commercial and industrial load) as shown in Figure 36.

Figure 36: 2024 hourly average load distribution without ToU tariff



Simulating ToU scenarios

Applying ToU tariffs to the baseline scenario involves calculating the change in load for all categories as shown in Figure 37 using the provided equations:

$$\left[\frac{l_{new} - l_{baseline}}{l_{baseline}}\right]_{24\times1} = [PEM]_{24\times24} \times \left[\frac{\Delta c}{c_0}\right]_{24\times1}$$

$$\left[\frac{l_{new}}{l_{baseline}}\right]_{24\times1} = \left[\left[PEM \times \frac{\Delta c}{c_0}\right]_{24\times1} + 1\right]_{24\times1}$$

To calculate the l_new for nth hour of the day:

$$[l_{new}]_n = \left[1 + \left(PEM \times \frac{\Delta c}{c_0}\right)\right]_n \times [l_{baseline}]_n$$

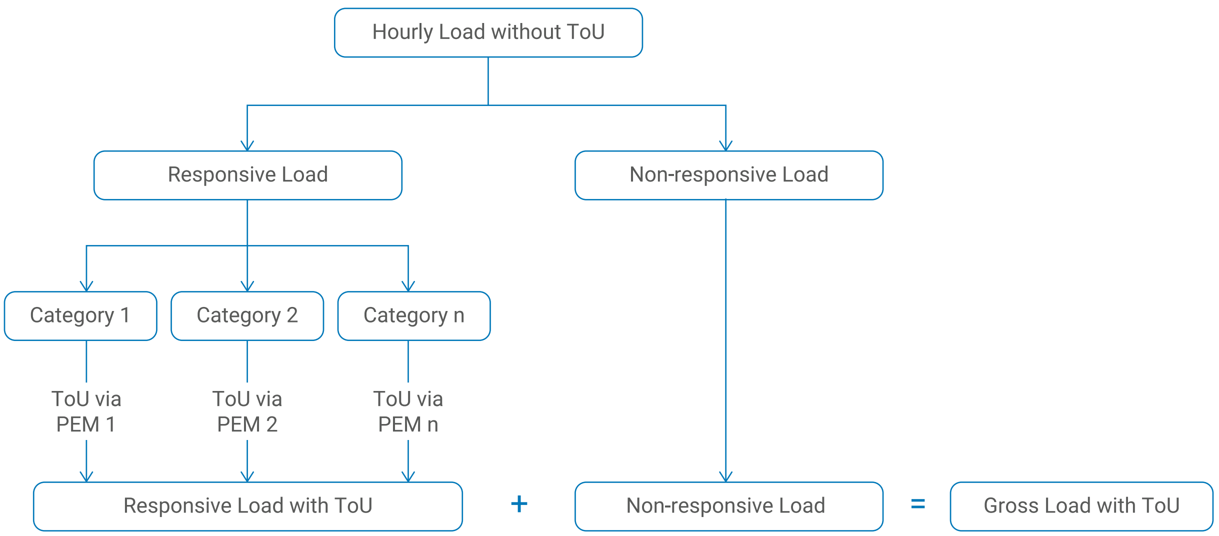
In a similar manner, the $\frac{l_{new}}{l_{baseline}}$ 24×1 matrix is iterated for all 365 days[3], effectively determining the new load for each of the 24 hours across the entire year.

[3] Although, 2024 has 366 days but the load and solar and wind generation forecasting was done for 365 days, skipping forecasting for 29/02/2024.

Where,
PEM represents 24×24 price elasticity matrix.
l_new signifies the new load after the application ToU for the nth hour.
l_baseline denotes the baseline load, namely, the load without ToU for the same nth hour.
Δc/c_ represents the matrix that encapsulates the ratio of the change in price to the initial price. This 24×1 matrix plays a pivotal role in determining the characteristics of peak hours, peak tariffs, off-peak hours, off-peak tariffs, and normal hours. Essentially, the values input into this matrix dictate the various tariff-based fluctuations.

This approach was then leveraged to generate distinct scenarios by varying the Δc/c_ matrix. Each of these cases encapsulated different combinations of peak hours, peak tariffs, off-peak hours, and off-peak tariffs. The computation process for every individual case followed the procedure outlined in the Figure 37 By systematically altering the values within the Δc/c_ matrix, we were able to generate these diverse scenarios, and load analysis of these scenarios shed light on the load behaviour under different tariff arrangements.

Figure 37: Computation flow chart



12

Glossary of Terms

Coincidence factor: It is the peak of a system divided by the sum of the peak loads of its components. It tells how likely the individual components are peaking at the same time. The highest possible coincidence factor is 1 when all of the individual components are peaking at the same time.

Cross-Elasticity: Cross-elasticity is used to measure the impact of price changes in a multi-period on electricity demand.

Demand Response: Demand response is a mechanism that encourages consumers to adjust their electricity usage in response to price signals or grid conditions. It involves reducing or shifting energy consumption during times of high demand or supply constraints to maintain grid stability and optimize overall energy efficiency.

Demand side management: Demand side management refers to the strategies and techniques used to control and modify the patterns of energy consumption by end-users. It involves measures such as adjusting energy usage during peak demand periods, implementing energy-efficient practices, and utilizing smart grid technologies to optimize energy consumption and reduce strain on the grid.

Frequency Distribution of the Load: The frequency distribution of the load is a graphical representation of the number of load points that occur at different levels of demand. In this method, the highest and lowest load of the year is divided into 10 segments, with the top segment representing the top 10% of the load, the bottom segment representing the bottom 10% of the load, and the segments in between representing the in-between. The frequency of occurrences of load points in each segment is then plotted for both the total load and the net load, providing a visual representation of how the load is distributed over time.

Load minus Solar: Load minus Solar is the total load subtracted by the solar generation.

Load minus Wind: Load minus Wind is the total load subtracted by the wind generation.

Load factor: It is the average load of a system divided by its peak load. The higher the load factor is, the smoother the load profile is, and the more the infrastructure is being utilised. The highest possible load factor is 1, which indicates a flat load profile.

Net load: 'Net load' refers to the electricity demand that must be met by conventional power plants as it is determined by subtracting the variable solar and wind generation from gross load.
Gross load: Goss load is the grid load not taking in to account solar and wind energy grid injection.

Net zero: Net zero refers to a state in which the greenhouse gases going into the atmosphere are balanced by removal from the atmosphere.

Non-Responsive Hours: Non-Responsive Hours are the period during which it is assumed that there will be no change or shifting of the electricity load. In this work, we have assumed that the non-responsive hours are 1:00h, 2:00h, and 3:00h of the overnight hours when most people are asleep.

Off-peak hours: Off-peak hours, on the other hand, are the periods when electricity demand is relatively lower.

Peak hours: Peak hours refer to the periods during the day when electricity demand is at its highest.

Price elasticity: Price elasticity is a normalized measure (for the relative price change) of the intensity of how the usage of a good (in this case electricity) changes when its price changes by one percent. It facilitates a comparison of the intensity of load changes among customers, since the price change has been factored out; the price elasticity is a relative measure of response.

Responsibility factor: It is a load of an individual component at the time of system peak divided by the peak load of this individual component. The responsibility factor tells how much of a component's peak load (in percentage) contributes to the system peak. When a component peaks at the same time as the system, its responsibility factor is 100%.

Renewable Purchase Obligation: Renewable Purchase Obligation (RPO) mandates that all electricity distribution licensees should purchase or produce a minimum specified quantity of their requirements from Renewable Energy Sources. This is as per the Indian Electricity Act, of 2003.

Ramping-up and Ramping-down: The ramp-up or down is calculated by the change in load divided by the change in time. The resulting positive value indicates a ramp-up and a negative value indicates a ramp-down.

Self-Elasticity: Self-elasticity is used to measure the impact of current price changes in a single period on electricity demand.

Time of Use Tariffs: Time of use tariffs, also known as time-varying pricing, are electricity pricing structures where the cost of electricity varies based on the time of day or day of the week. The aim is to incentivize consumers to shift their electricity usage to off-peak periods, reducing strain on the grid and promoting more efficient use of energy.

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