PONDAGE: ENGINEERING ANALYSIS

Peter Rae

Indus Waters Western Rivers Arbitration (Pakistan v. India)
PCA Case No. 2023-01

Hearing for the Second Phase on the Merits

2 February 2026

Part I

Introduction

Award Background (1)

> 746. *First*, "Firm Power", shall be calculated as the hydro-electric power corresponding to the MMD at the site of the plant, calculated in accordance with Paragraph 2(i) of Annexure D.

General Issues Award, ¶ 746

- **Firm Power is computed for the MMD at the site. The other inputs being the net generating head, turbine-generator efficiency, and other physical parameters.**
- **Firm Power is interpreted as being equivalent to total energy available from continuous generation during a 168-hour week.**
- **Pondage determines how the available energy can be used within a power system.**

Award Background (2)

747. *Second,* "Pondage required for Firm Power" shall be calculated based on the water that can be accumulated and released at the site of the plant during the course of no more than a seven-day period, within the following constraints:

(a) Pondage required for Firm Power shall be calculated based on what can be accumulated during that period when the stream flow of the river is at the MMD, as set forth in Paragraph 2(i) of Annexure D.

(b) Pondage required for Firm Power shall be calculated based on a realistic, well-founded, and defensible projection of the proposed Annexure D, Part 3 HEP's installed capacity and anticipated load, reflecting the fluctuations in the discharge of the turbines arising from variations in the daily and weekly loads of the plant, as set forth in Paragraph 2(c) of Annexure D.

(c) Pondage required for Firm Power shall be calculated in a manner that abides by the daily and weekly release requirements set forth in Paragraph 15 of Annexure D.

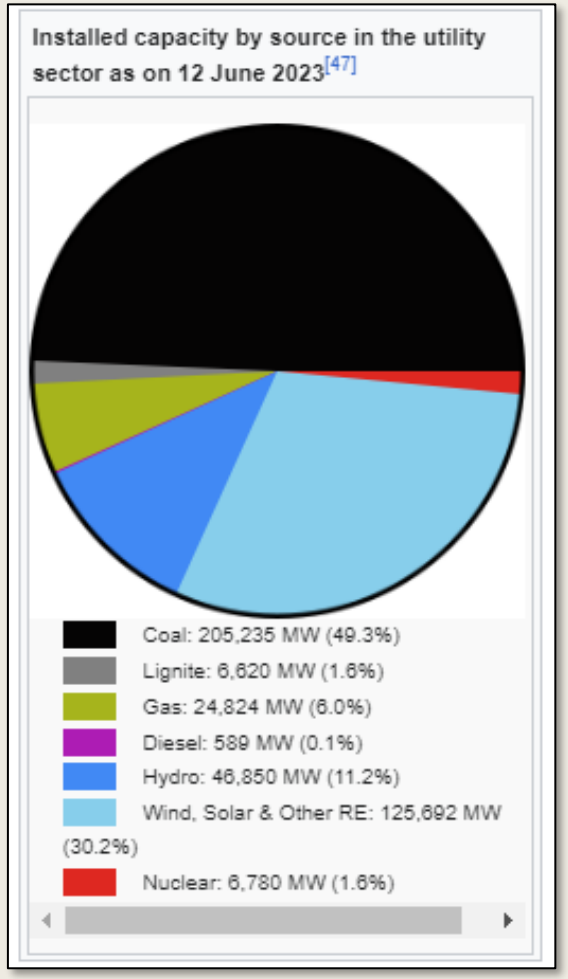
General Issues Award, ¶ 747

Part II

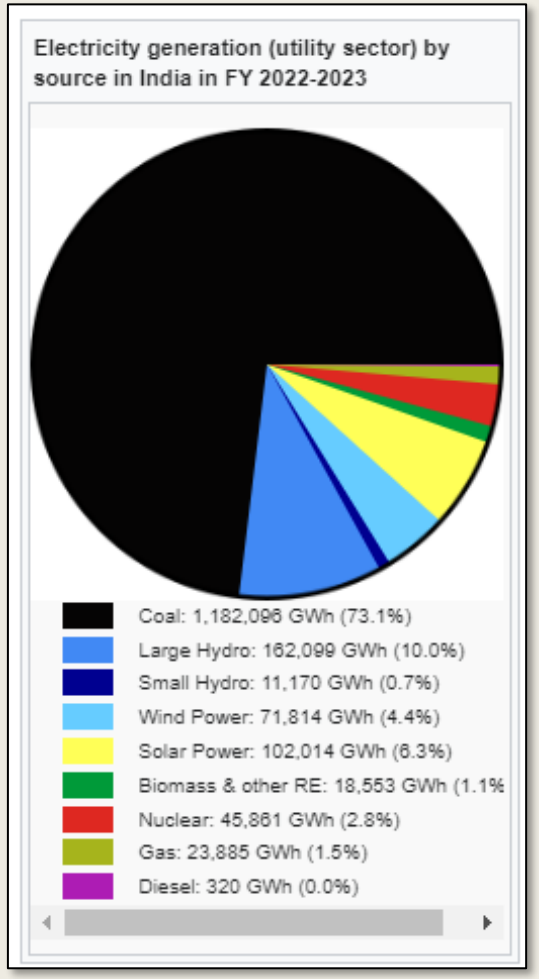
Anticipated Load in Power System in Northern Region of India

Power System in India

"Growth of Electricity Sector in India from 1947 – 2020", **P-0590**

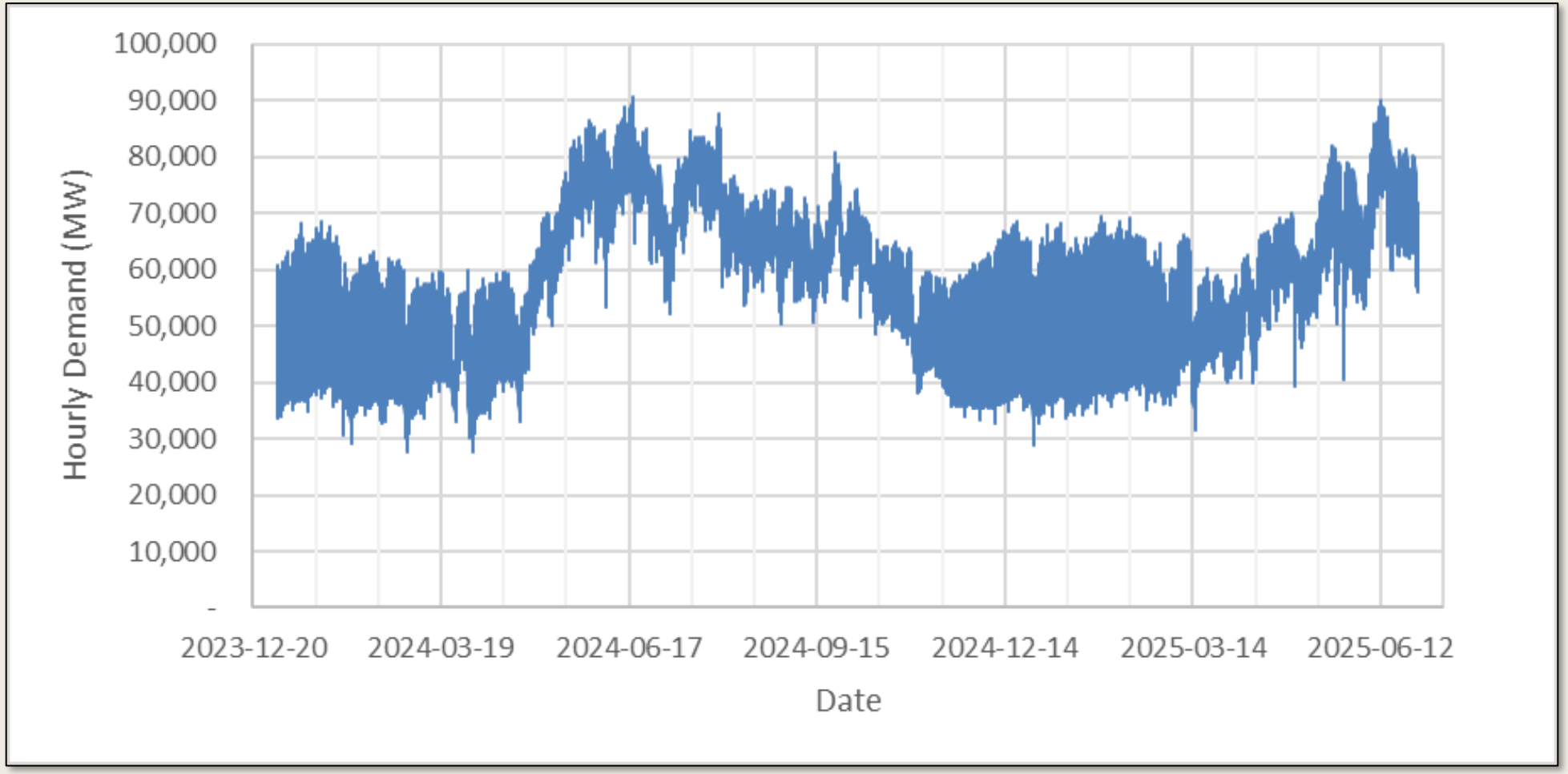


"Power Sector at a Glance, All India", **P-0593**



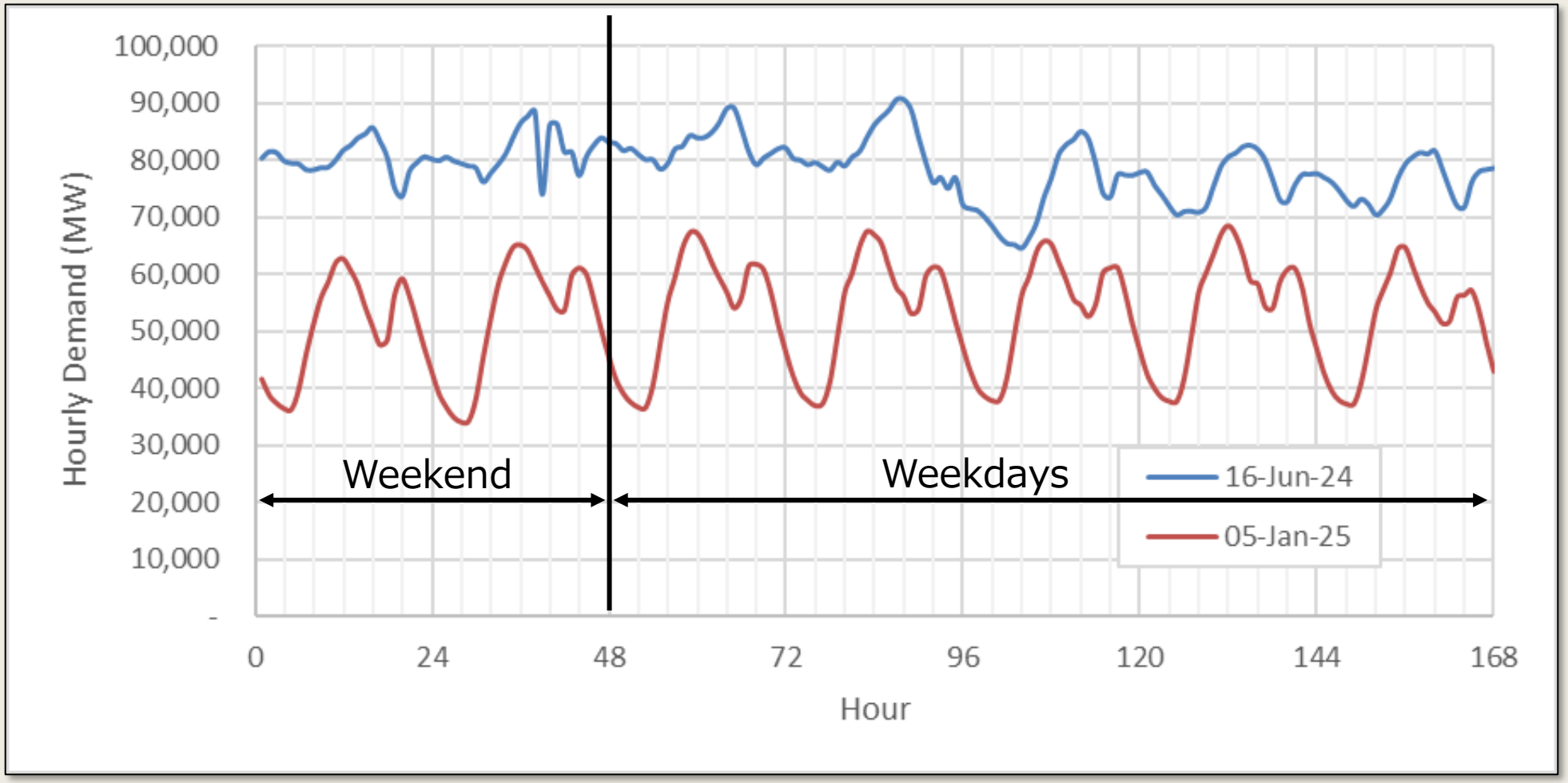
"Status of Pumped Storage Development in India", **P-0592**

Northern Region Power Demand



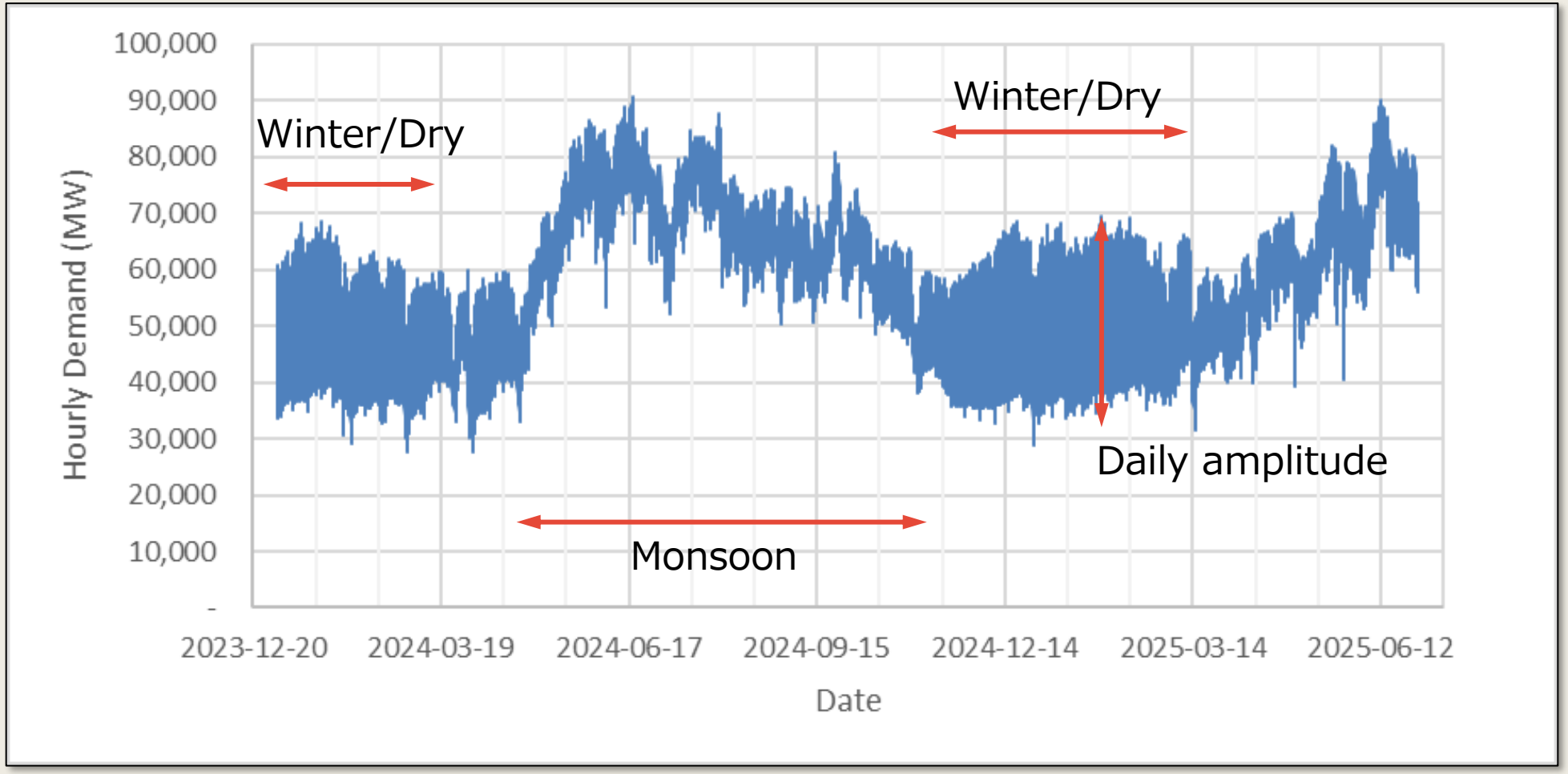
Second Phase Memorial, Appendix D, Figure 1 (based on hourly demand data for the Northern Region of India from 1 January 2024 to 30 June 2025, **P-0717**)

Within Week Power Variations



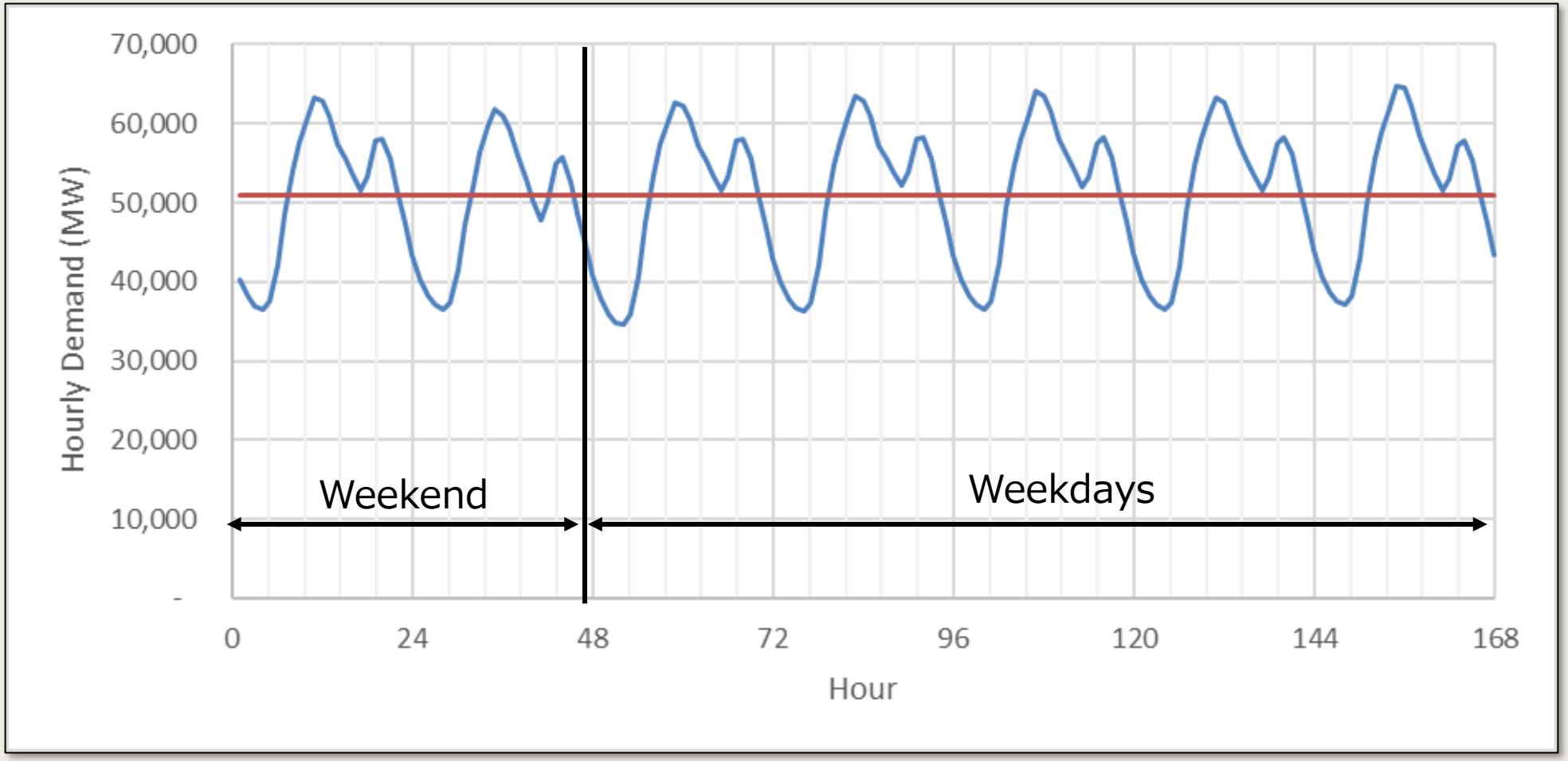
Based on hourly demand data for the Northern Region of India from 1 January 2024 to 30 June 2025, **P-0717**

Pondage is needed in the Dry Season



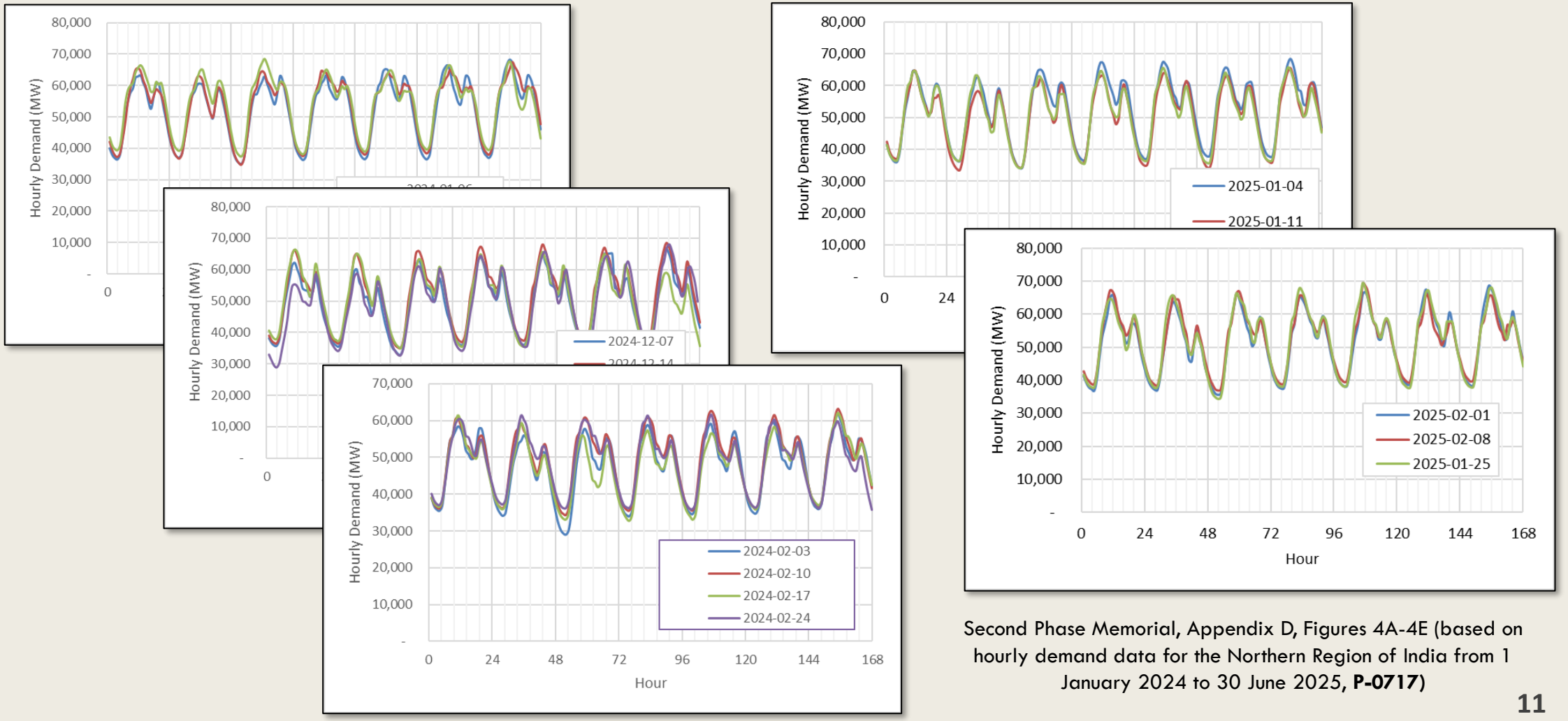
Second Phase Memorial, Appendix D, Figure 1 (based on hourly demand data for the Northern Region of India from 1 January 2024 to 30 June 2025, **P-0717**)

Average weekly load curve for Northern Region



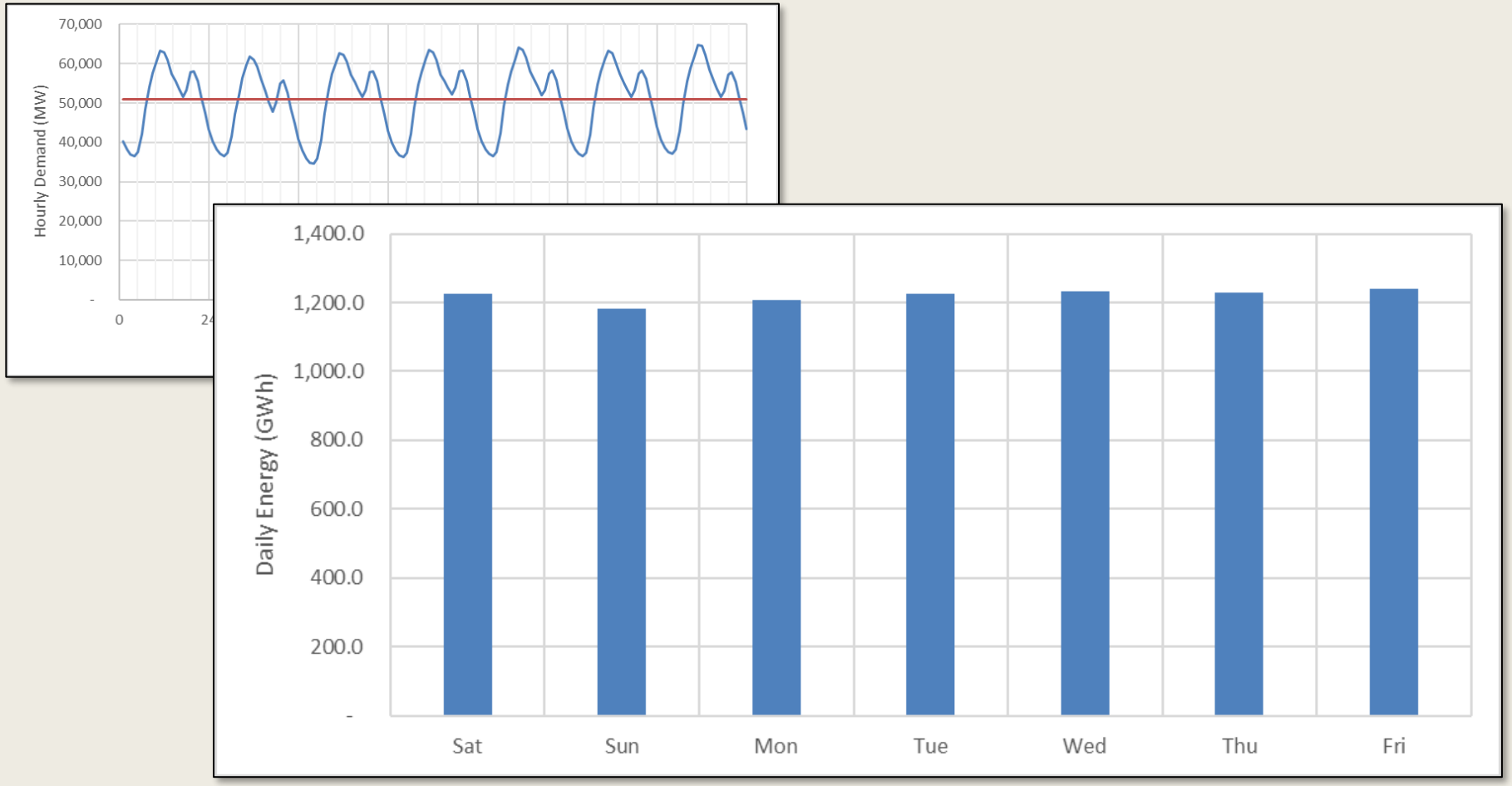
Second Phase Memorial, Appendix D, Figure 11 (based on hourly demand data for the Northern Region of India from 1 January 2024 to 30 June 2025, **P-0717**)

Variations in Weekly Load Curves for Northern Region



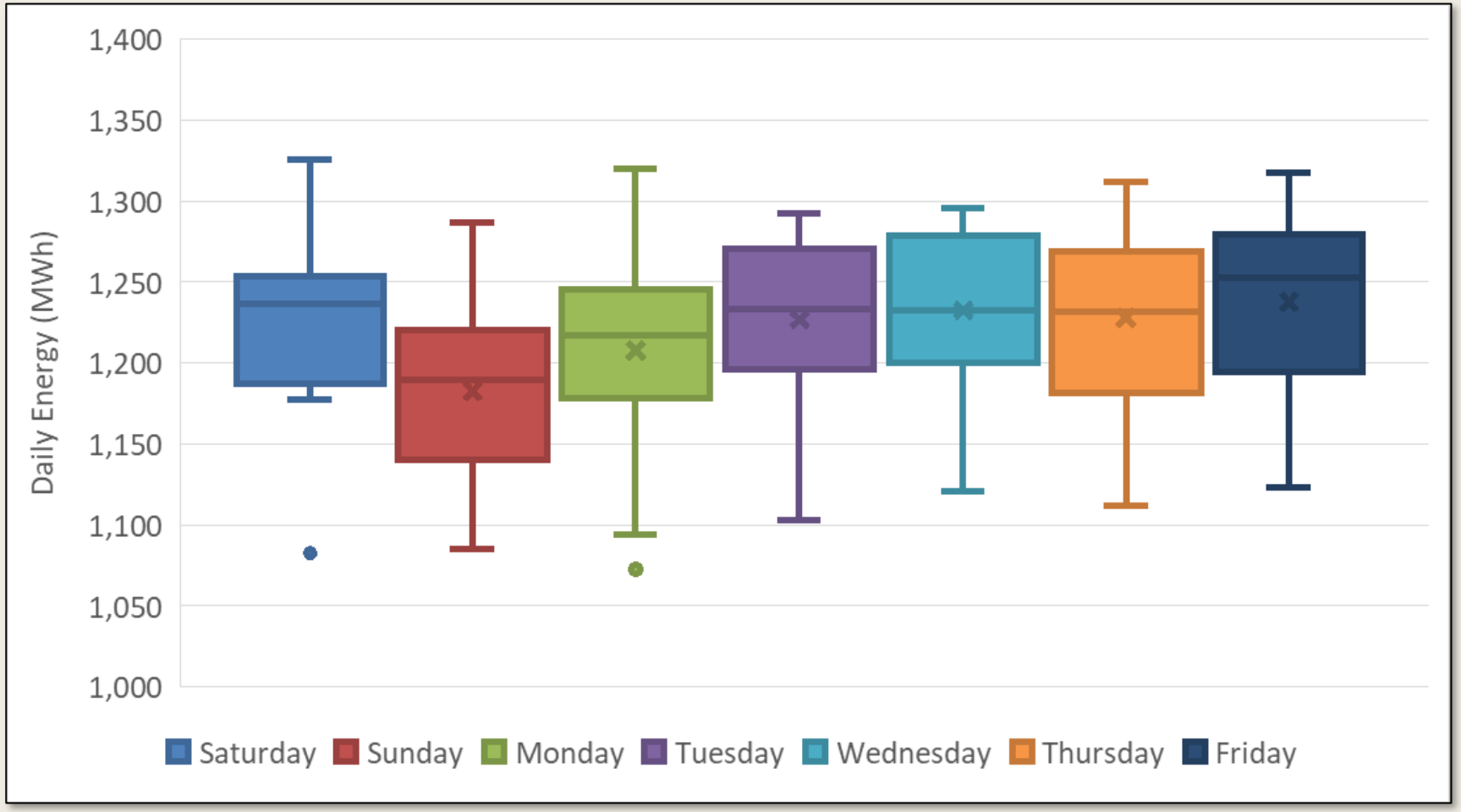
Second Phase Memorial, Appendix D, Figures 4A-4E (based on hourly demand data for the Northern Region of India from 1 January 2024 to 30 June 2025, **P-0717**)

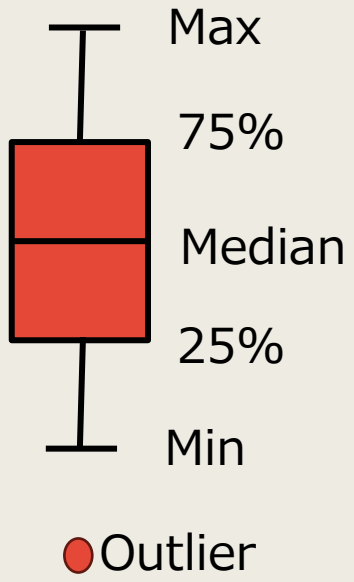
Weekly Energy Distribution (1)



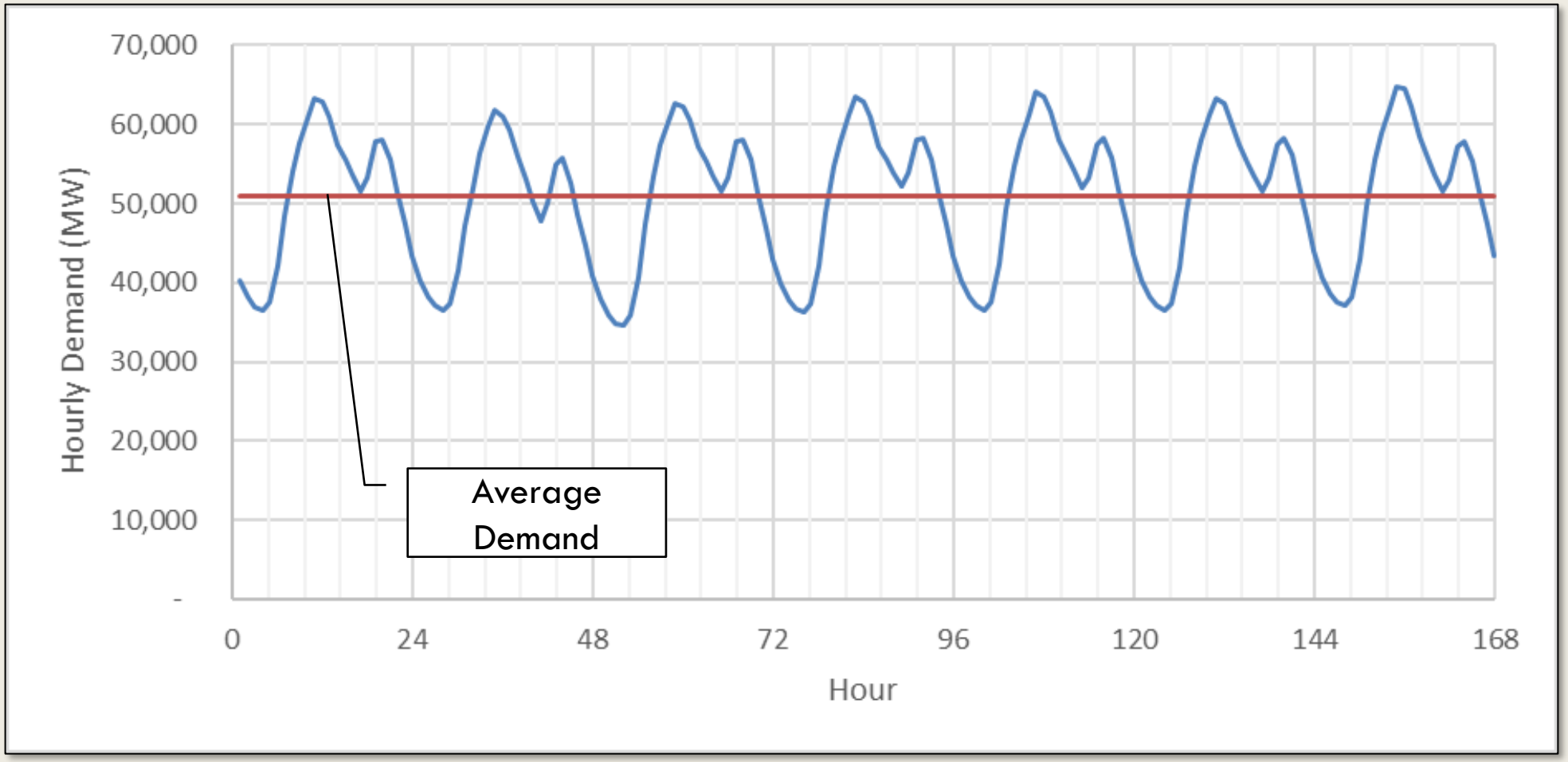
Second Phase Memorial, Appendix D, Figure 5

Weekly Energy Distribution (2)





Average weekly load curve for Northern Region



Second Phase Memorial, Appendix D, Figure 11 (based on hourly demand data for the Northern Region of India from 1 January 2024 to 30 June 2025, **P-0717**)

Part III

Installed Capacity and Pondage

Installed capacity: terminology

(*c*) Aggregate designed maximum discharge through the turbines.

(*d*) Maximum aggregate capacity of power units (exclusive of standby units) for Firm Power and Secondary Power.

Capacity/Power

$P_{IC}=P_F+P_S$

P_F Firm Power (MW)

P_S Secondary Power (MW)

P_{IC} Installed capacity or maximum aggregate capacity (MW)

Energy/Power

Firm Energy = P_F x 168 (MWh)

Secondary Energy depends on hydrology

Flow Rate/Volume

Q_F = MMD

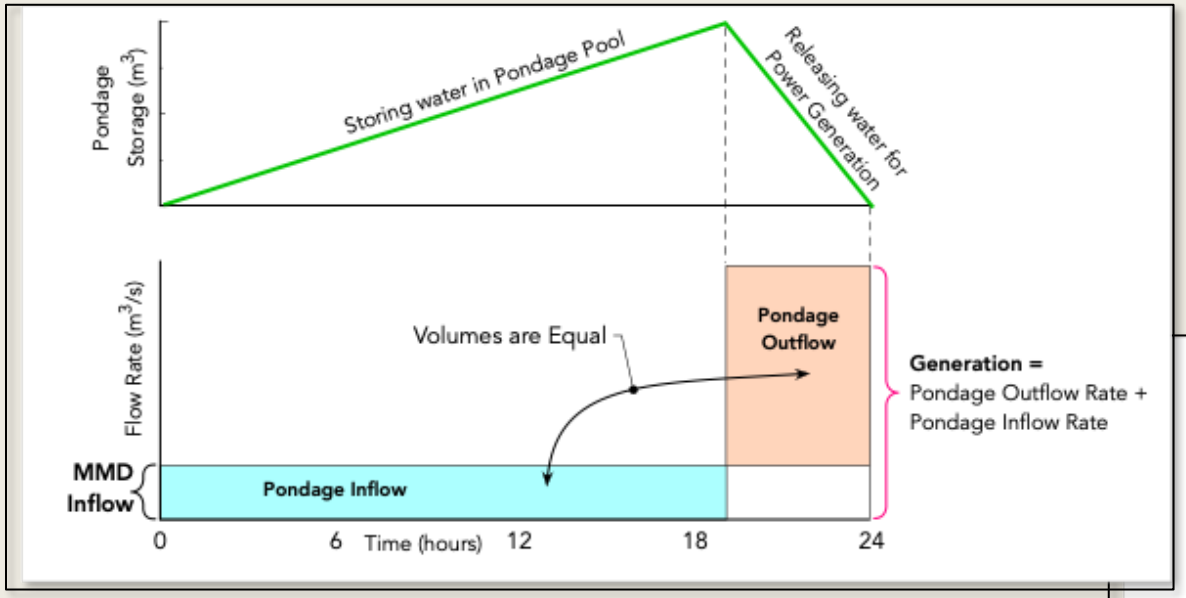
Vol_F = MMD x 168 (m^3/s-hrs)

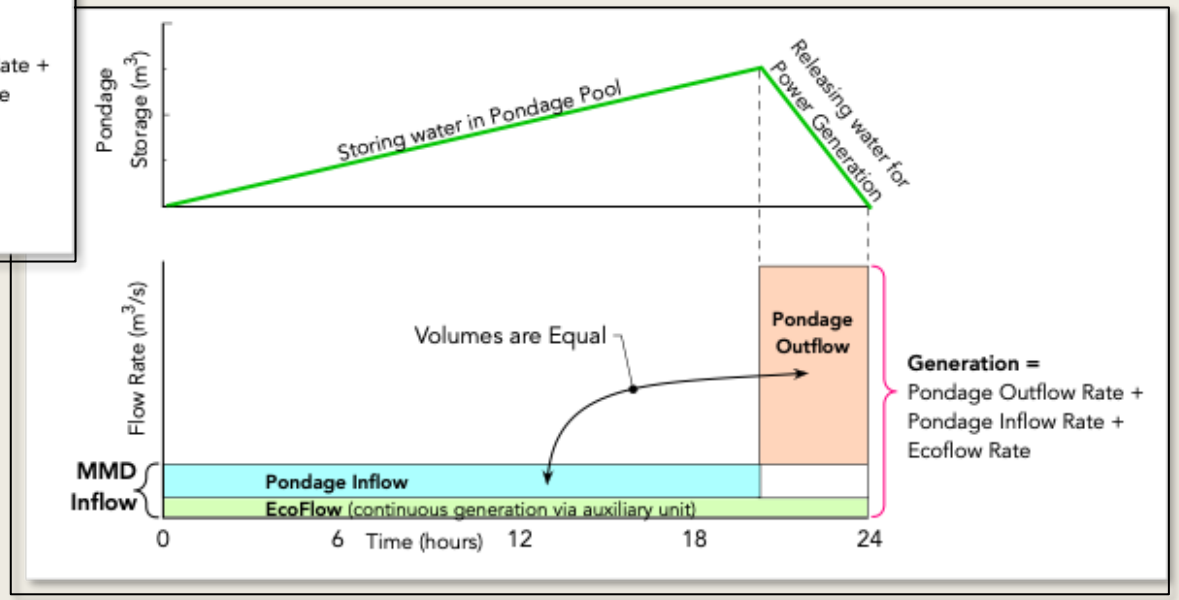
Installed Capacity

Maximum, theoretical power output in MW under specific conditions, including:

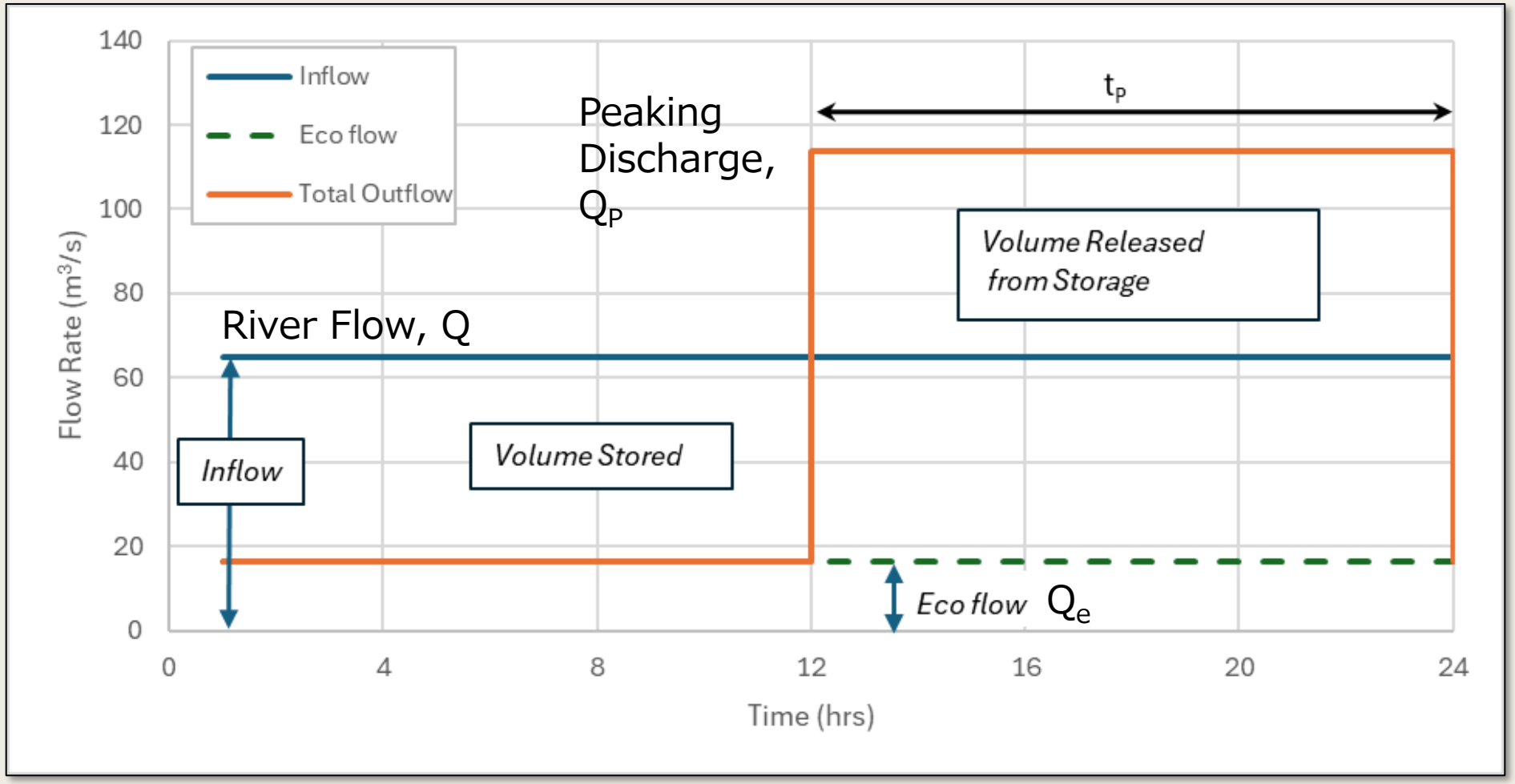
- Rated discharge
- Gross generating head
- Head losses
- Turbine/Generator/electrical efficiencies
- Fluid parameters

24-hour Relationship Between Pondage Filling and Outflow for Generation





Installed Capacity and Pondage (1)



Installed Capacity and Pondage (2):

Pondage calculation

$$t_p = \frac{Q \times 24}{Q_p}$$

$$V_p = Q \times (24 - t_p) \times 0.0036$$

$$V_p = \left(24(Q - Q_e) - \frac{(24)(Q - Q_e)^2}{Q_p}\right) \times 0.0036$$

t_P Peaking time (hrs)

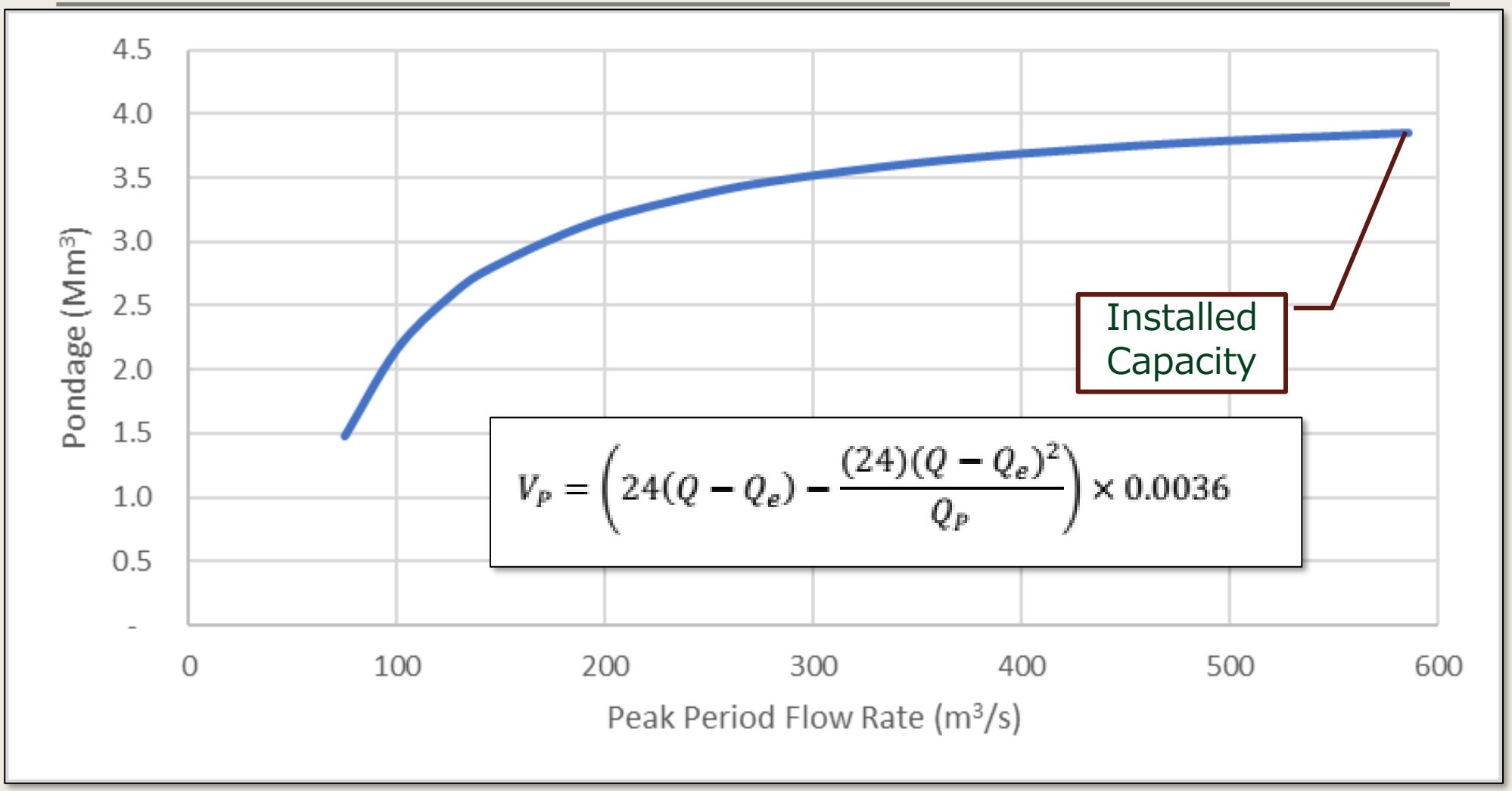
Q inflow (m^3/s)

Q_e Eco flow (m^3/s)

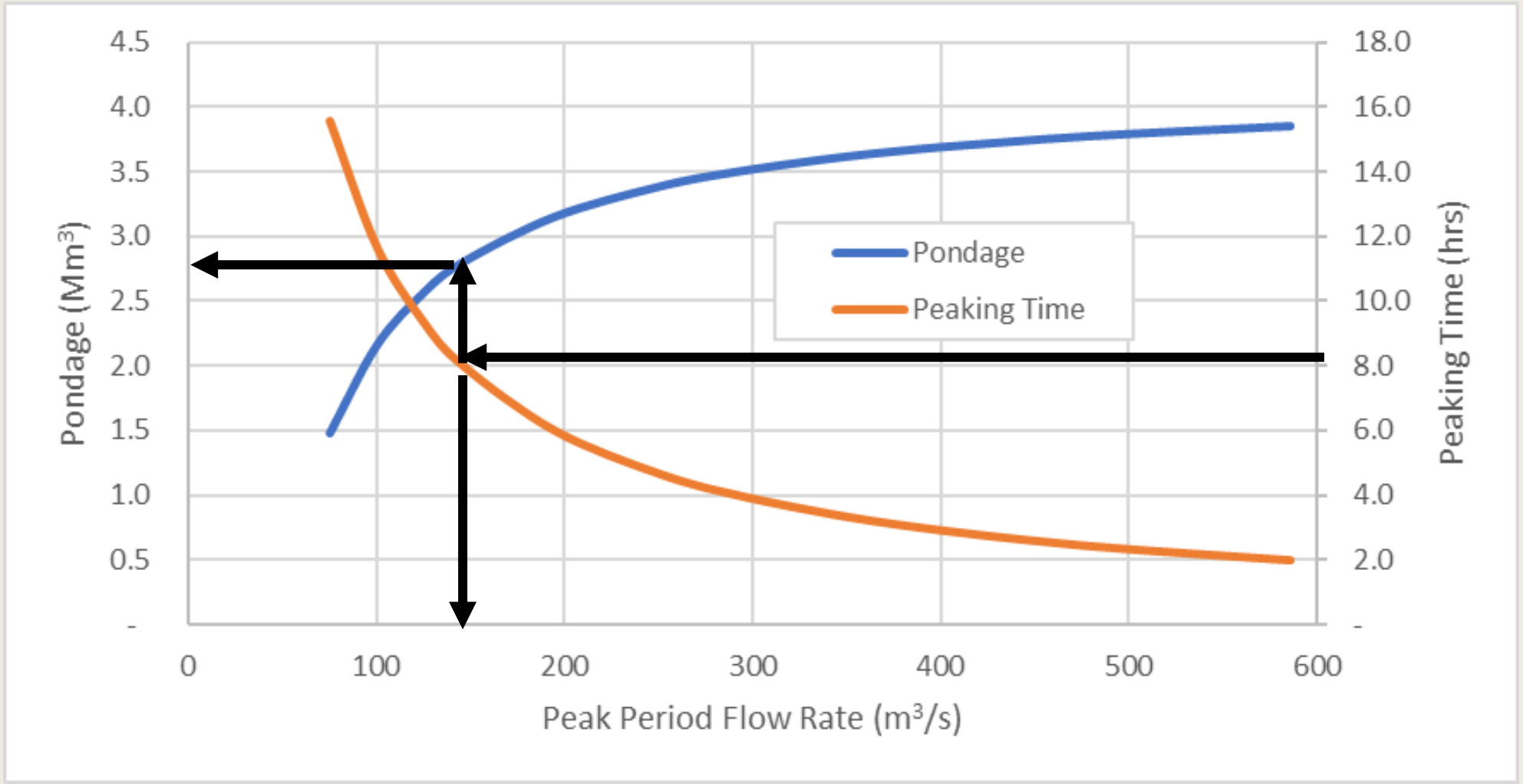
Q_P Peaking flow (m^3/s)

V_P Pondage (Mm^3)

Installed Capacity and Pondage (3)

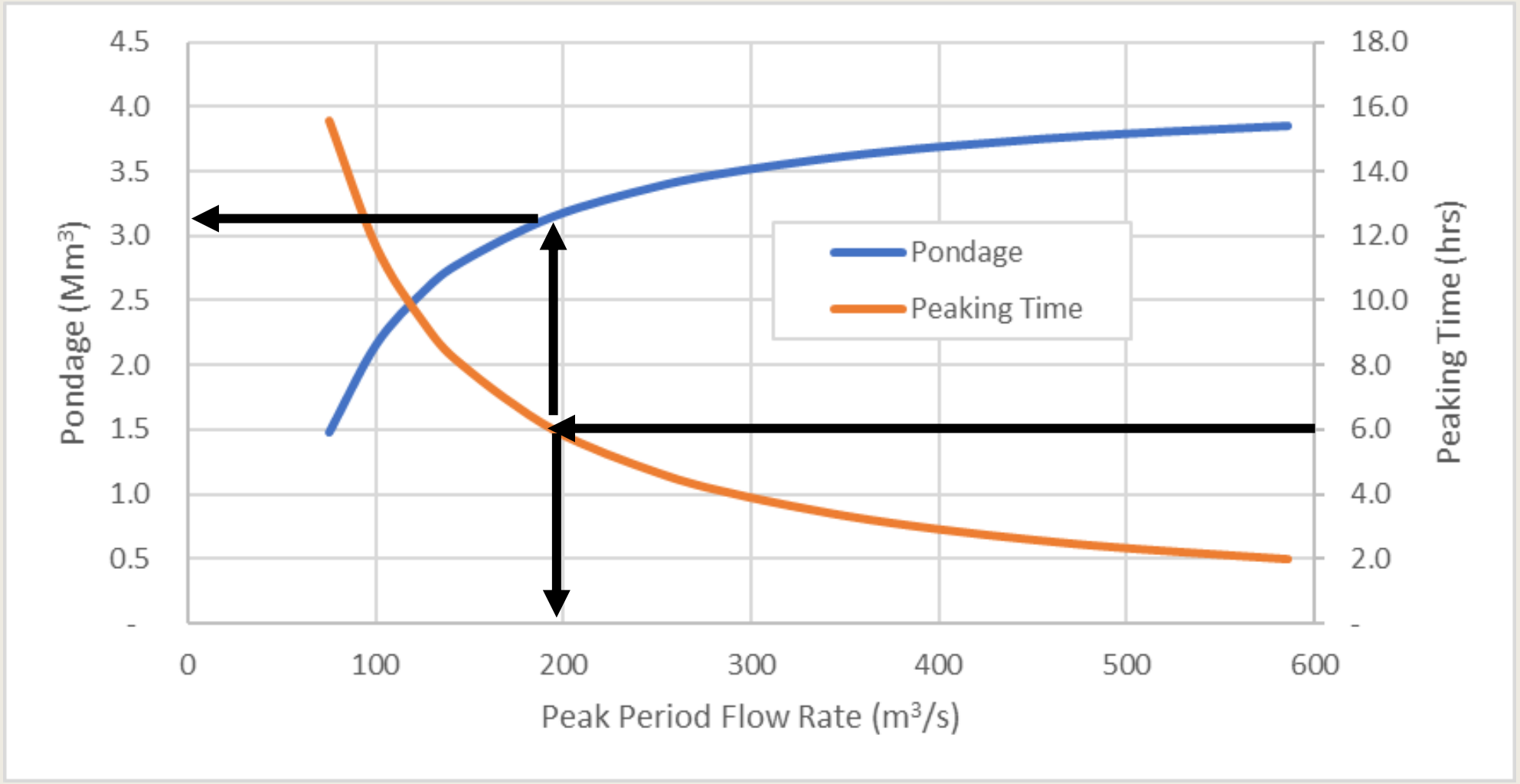


Installed Capacity and Pondage (4)



Second Phase Memorial, Appendix D, Figure 9

Installed Capacity and Pondage (5)

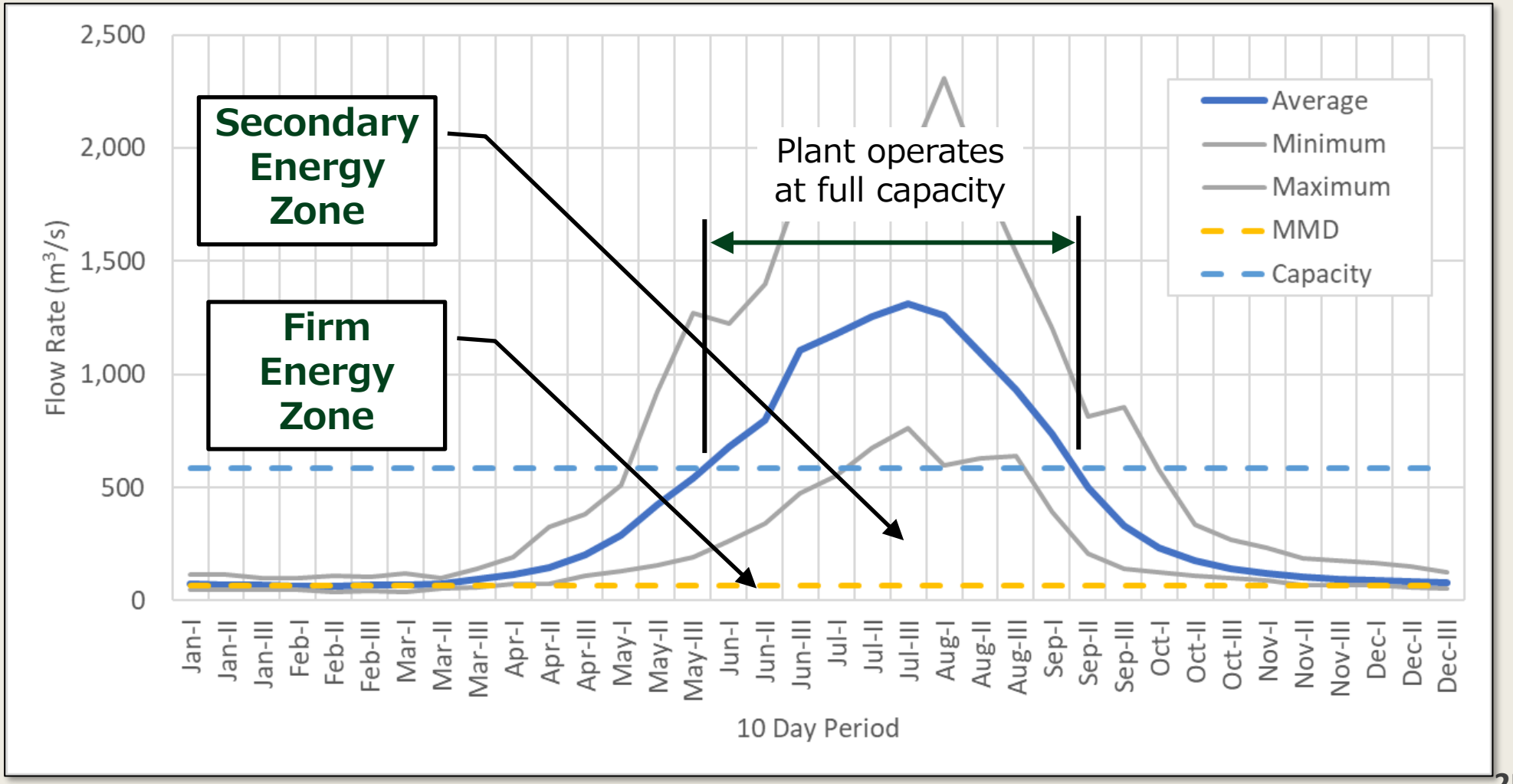


Second Phase Memorial, Appendix D, Figure 9

Part IV

Plant Operation

Seasonal Operating Ranges



Based on daily flow data for the Kiru HEP site, **P-0546**

Unit Outages

Annual
(2-3 weeks)

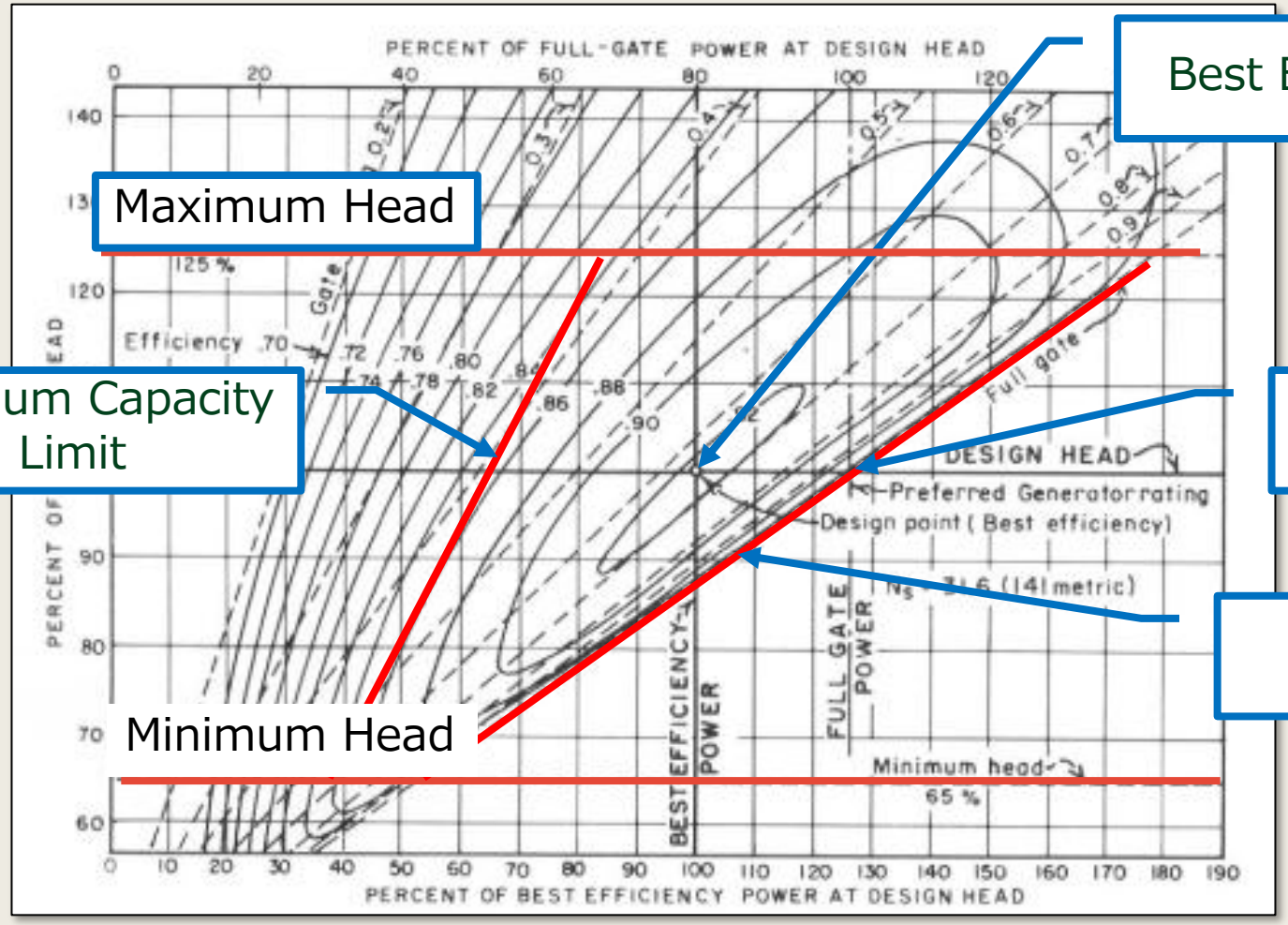
- Inspections
- Sediment repairs
- Minor preventative maintenance

Major Preventative Maintenance
(4 – 6 weeks)

Overhaul and Replacements
(5 to 8 months)

USACE, *Hydropower*, **P-0302 (resubmitted)**, 2-11, p. 346; ASME, "The Guide to Hydropower Mechanical Design", **P-0716**

Turbine Limits: Best Efficiency



Best Efficiency

Maximum Head

Minimum Capacity Limit

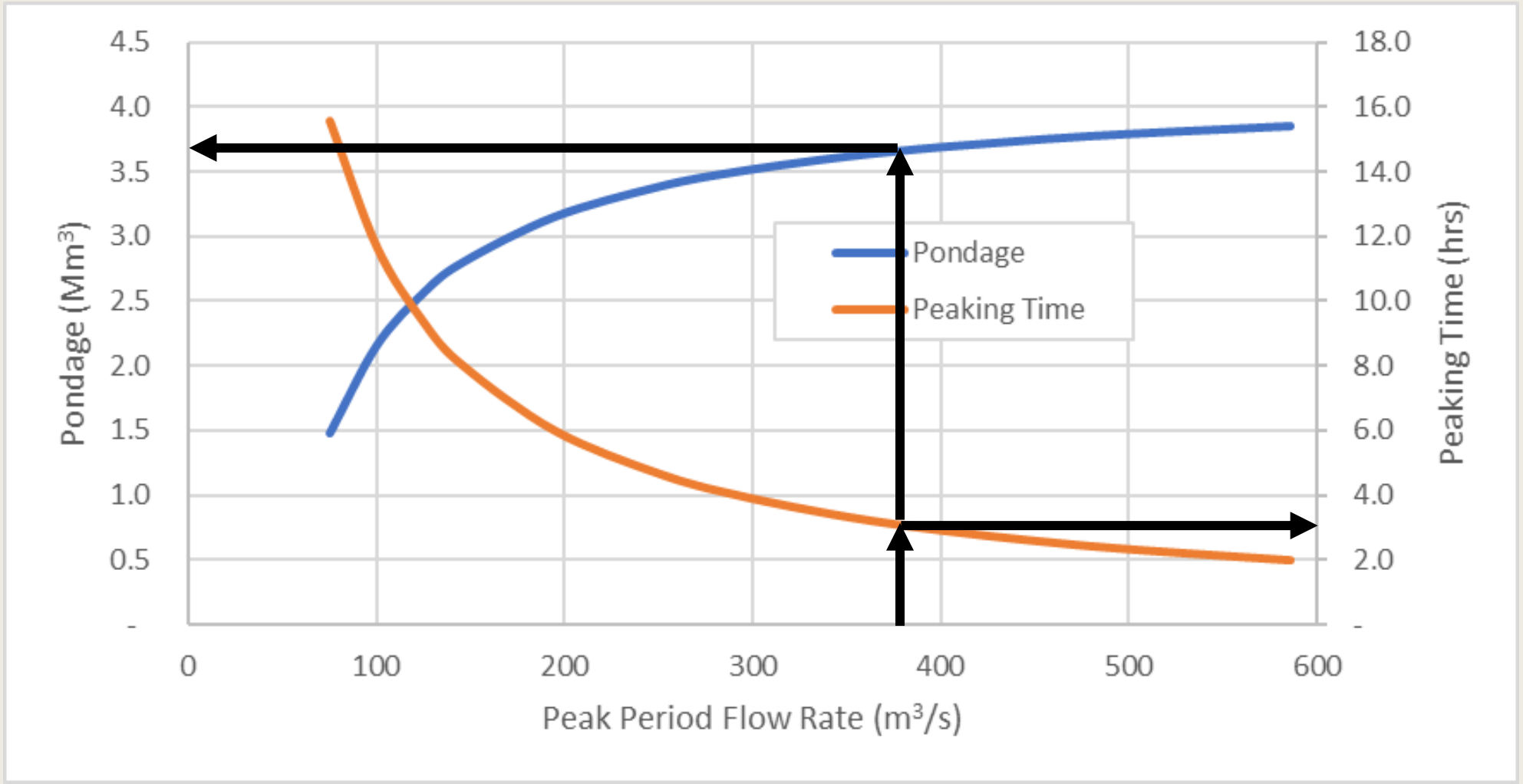
Installed Capacity

Capacity Limit

Minimum Head

United States Department of the Interior, Bureau of Reclamation, "Selecting Hydraulic Reaction Turbines", **P-0720**

Pondage and Adjusted Capacity

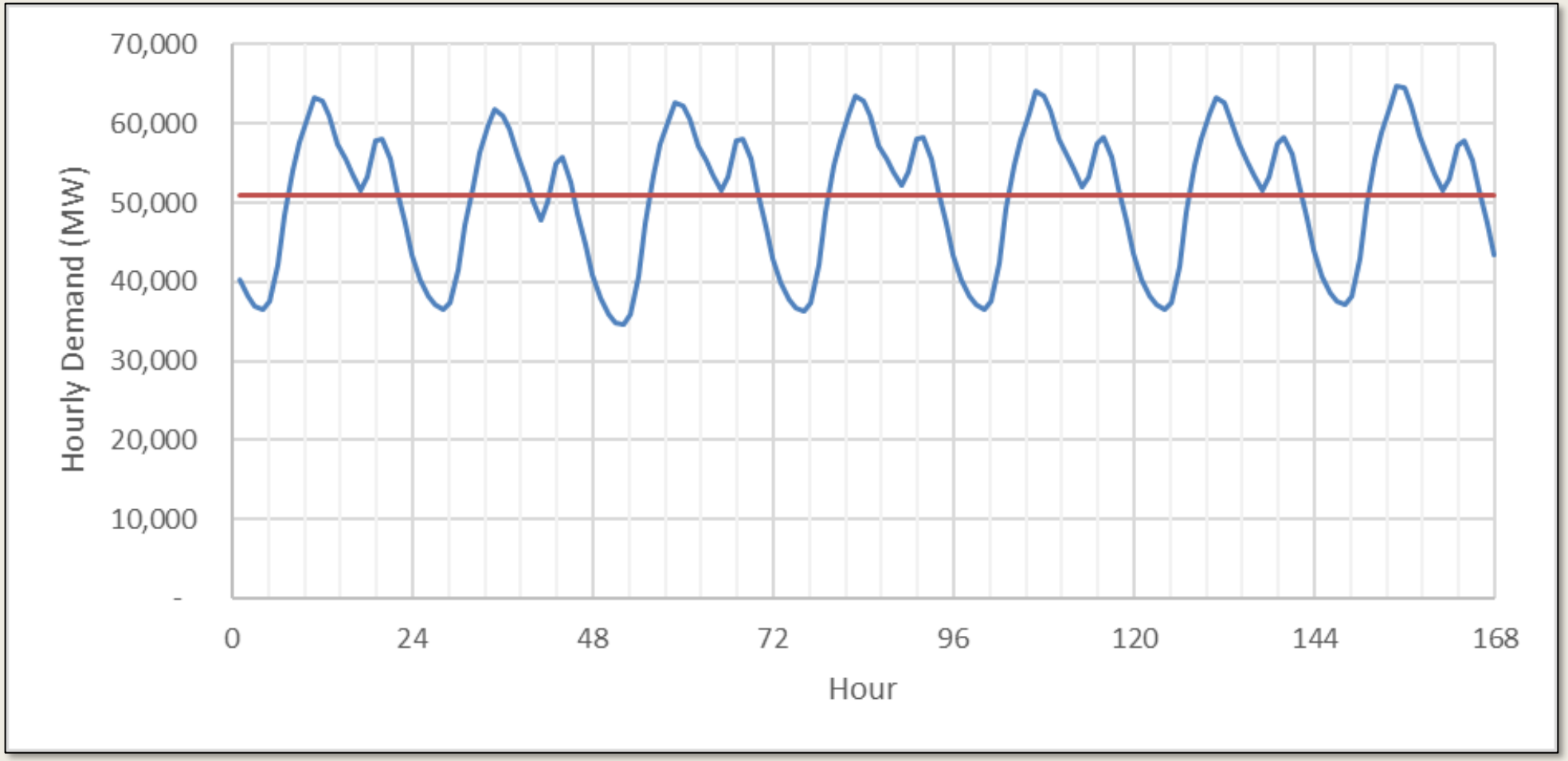


Second Phase Memorial, Appendix D, Figure 9

Part V

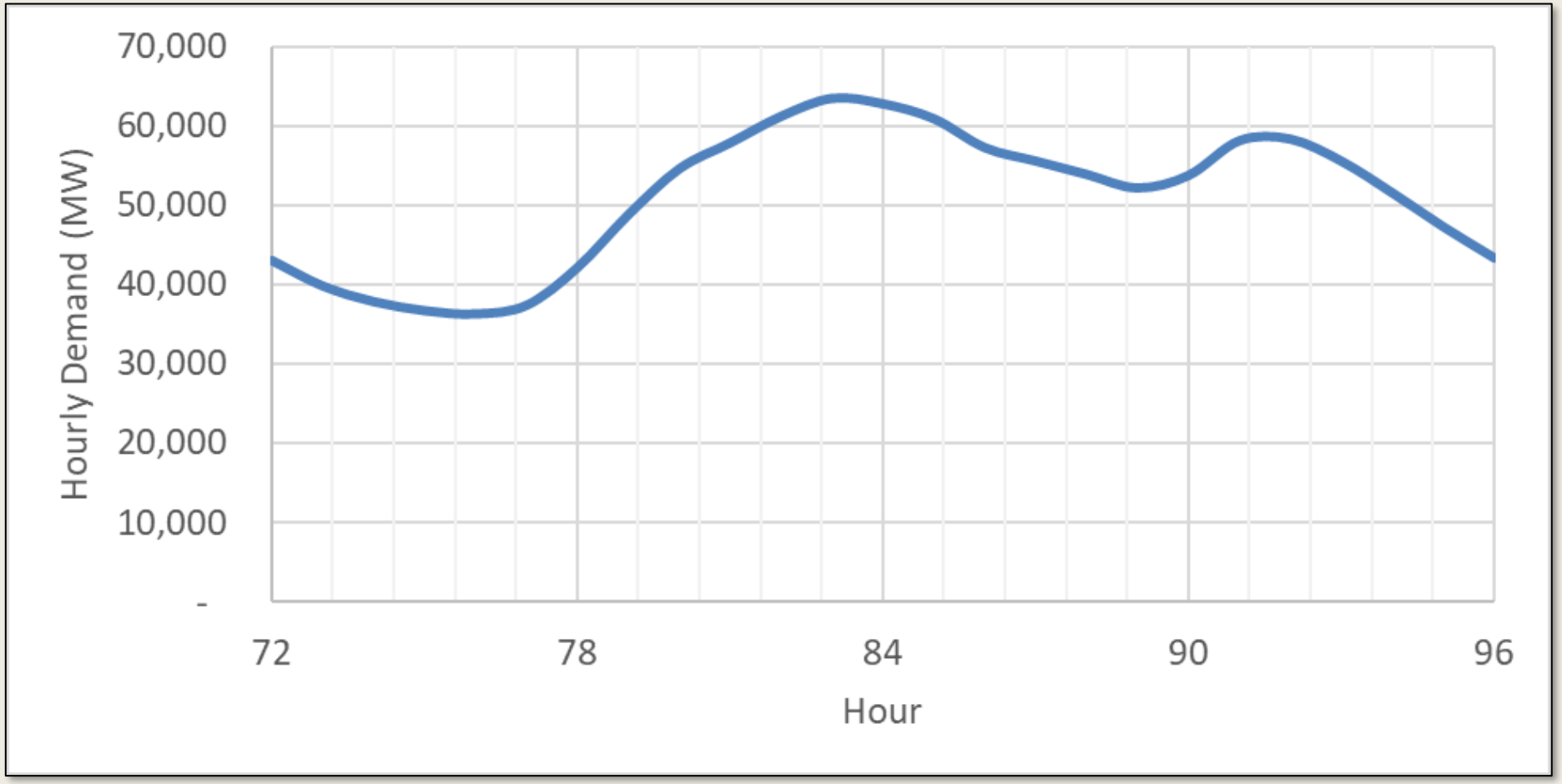
Power System Operation and Plant Dispatch

Average weekly load curve for Northern Region



Second Phase Memorial, Appendix D, Figure 11 (based on hourly demand data for the Northern Region of India from 1 January 2024 to 30 June 2025, **P-0717**)

Representative Daily Load Curve



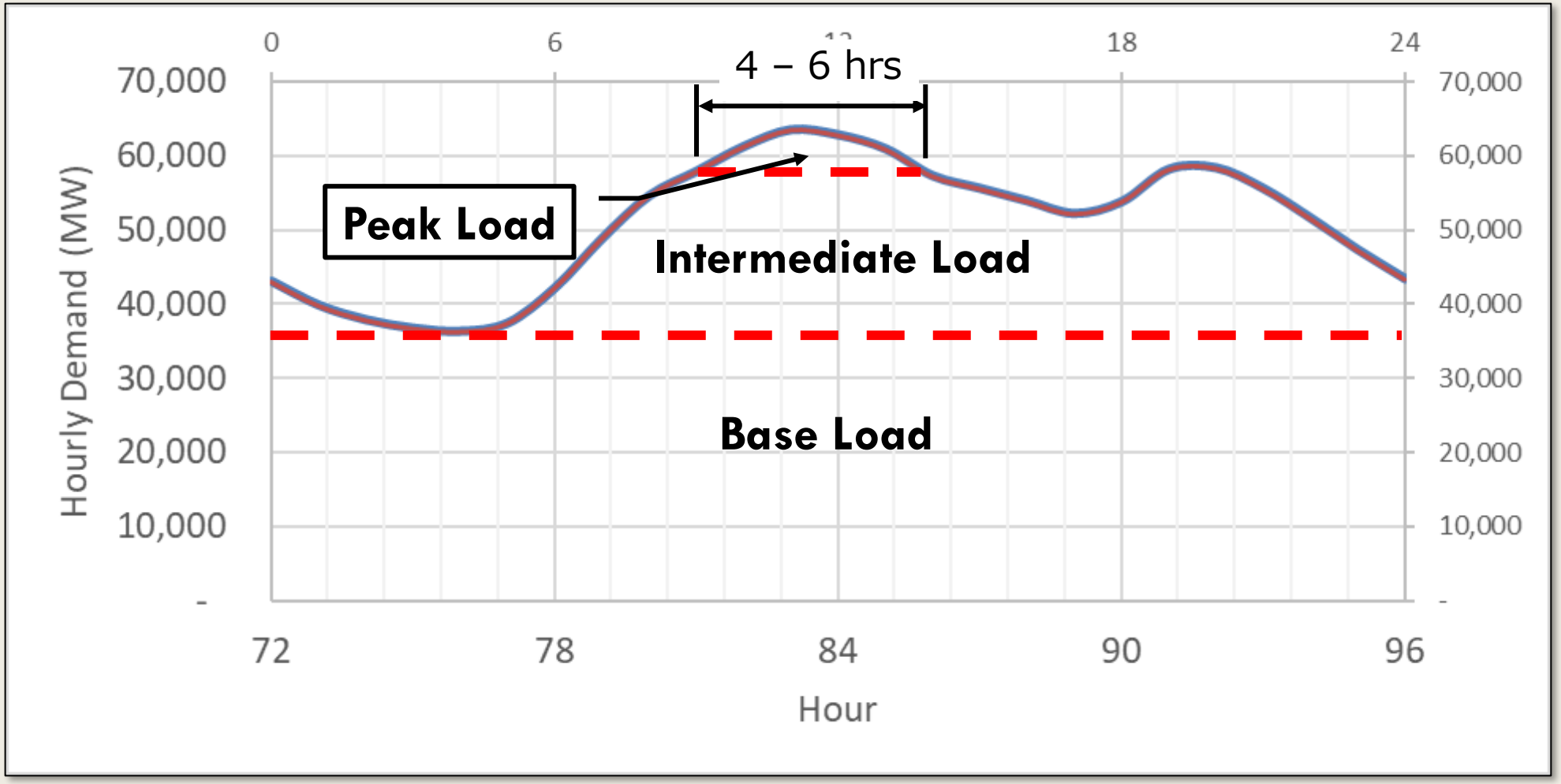
Plant Characteristics

Plant Type	Plant Factor	Daily Hours
Peaking	5 to 17%	4 to 8
Intermediate	17 to 40%	8 to 12
Base	Up to 90 - 100%	12 to 24

Plant Factor = Energy/(Power x Time)

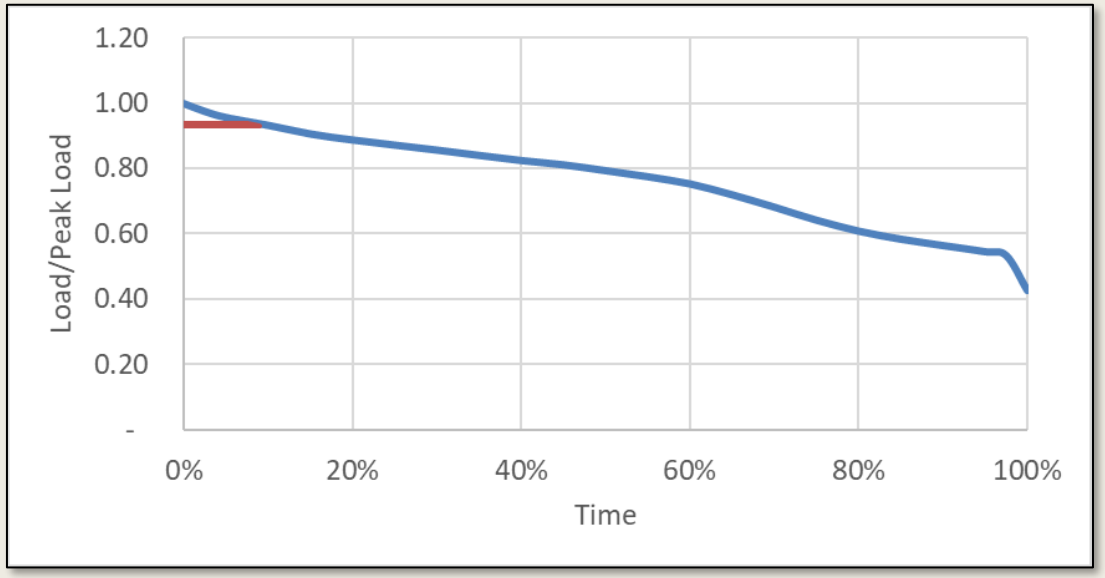
USACE, *Hydropower*, **P-0302 (resubmitted)**, S-6, p. 296

Daily Load


0
6
18
24
4 – 6 hrs
70,000
60,000
50,000
40,000
30,000
20,000
10,000
-
Hourly Demand (MW)
Peak Load
Intermediate Load
Base Load
72
78
84
90
96
Hour

Daily Dispatch Criteria

- Expected minimum peaking from Daily Load - about 4-6 hours
- Maximum based on minimum turbine flow – about 16 hours
- Theoretical minimum – about 2.2 hours
- Adjust for practical system dispatch
- Adjust for Paragraph 15 limits

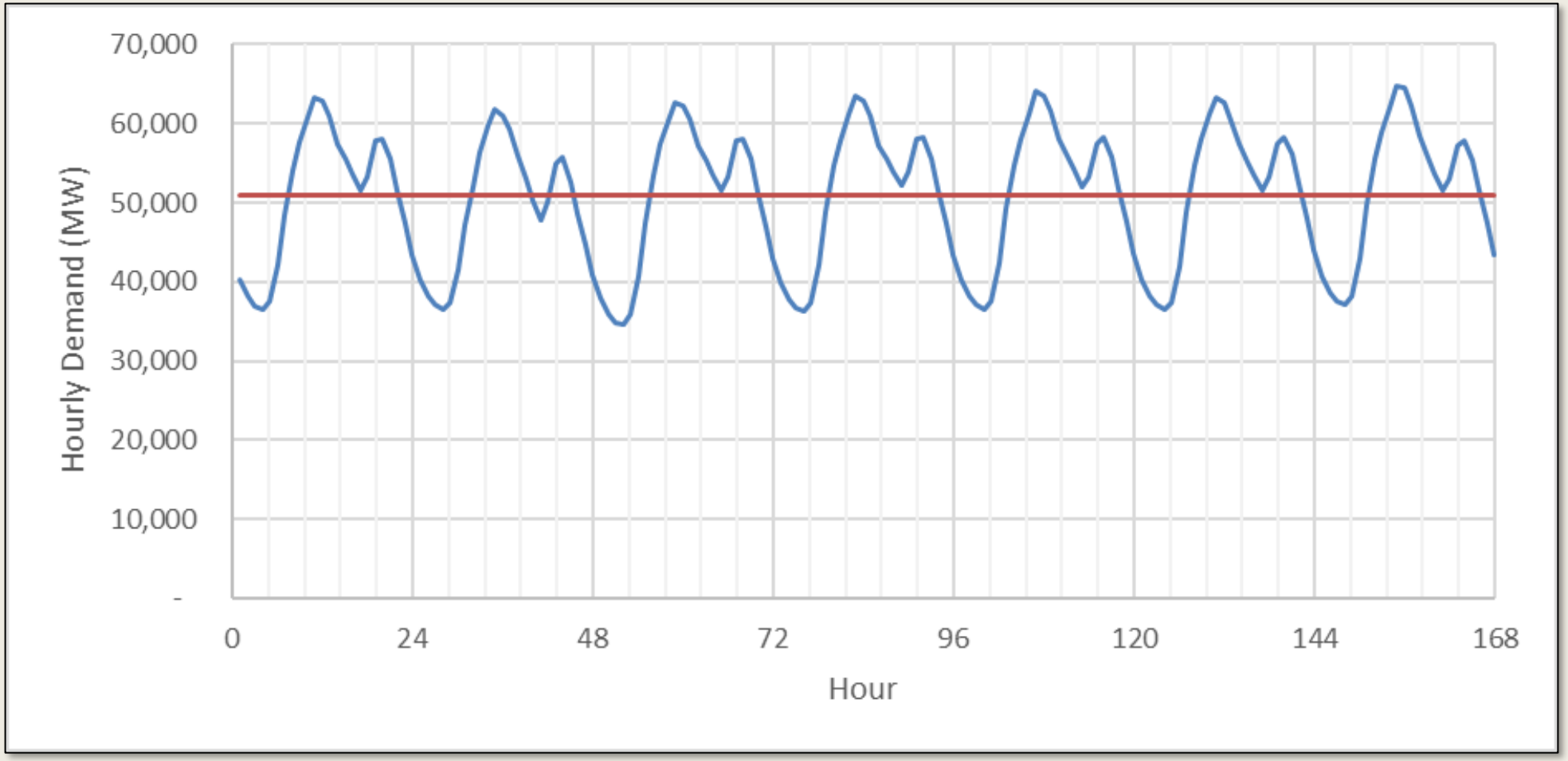


Second Phase Memorial, Appendix D, Figure 8

Part VI

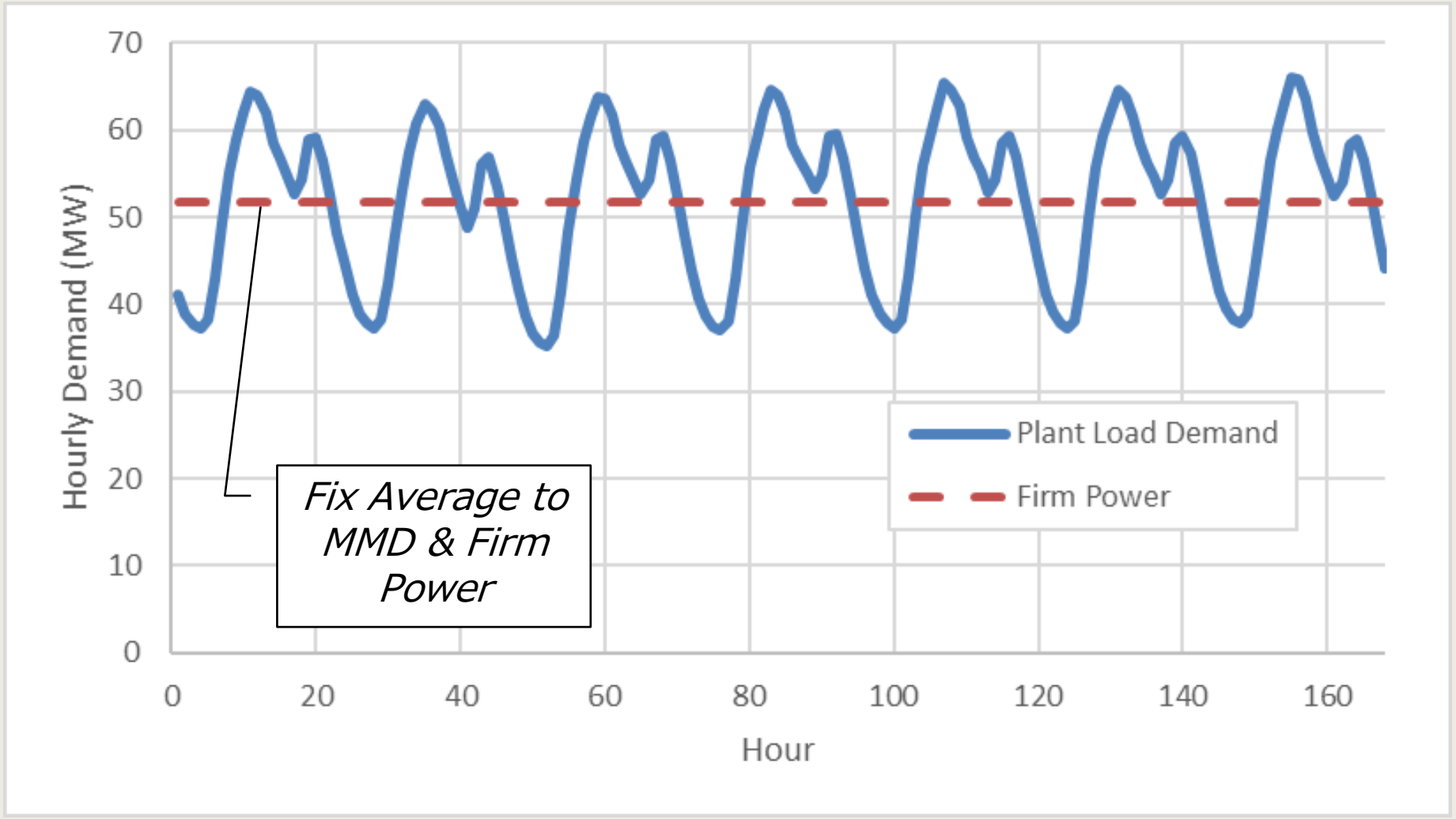
Weekly Pondage Analysis

Average weekly load curve for Northern Region

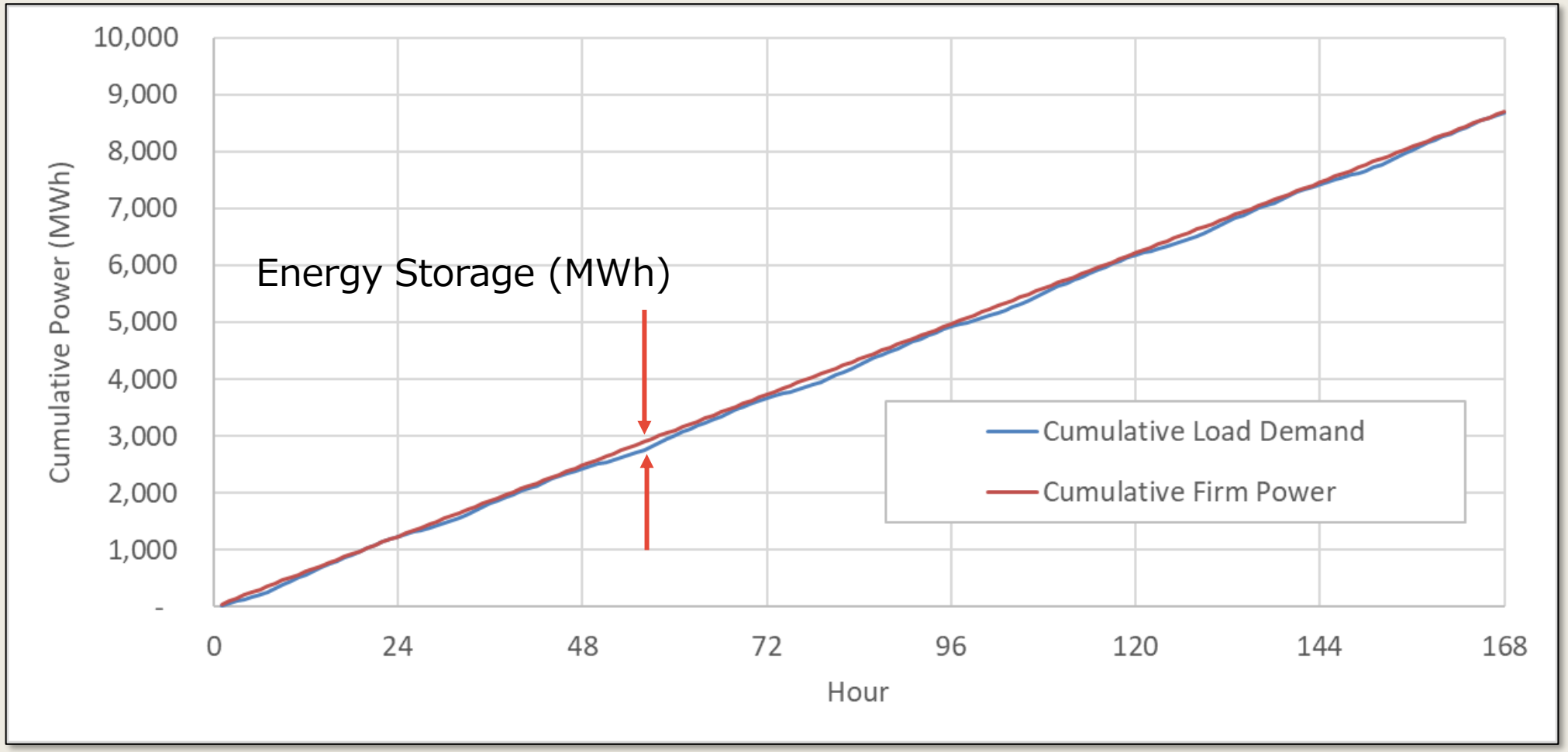


Second Phase Memorial, Appendix D, Figure 11 (based on hourly demand data for the Northern Region of India from 1 January 2024 to 30 June 2025, **P-0717**)

Kiru Weekly Demand



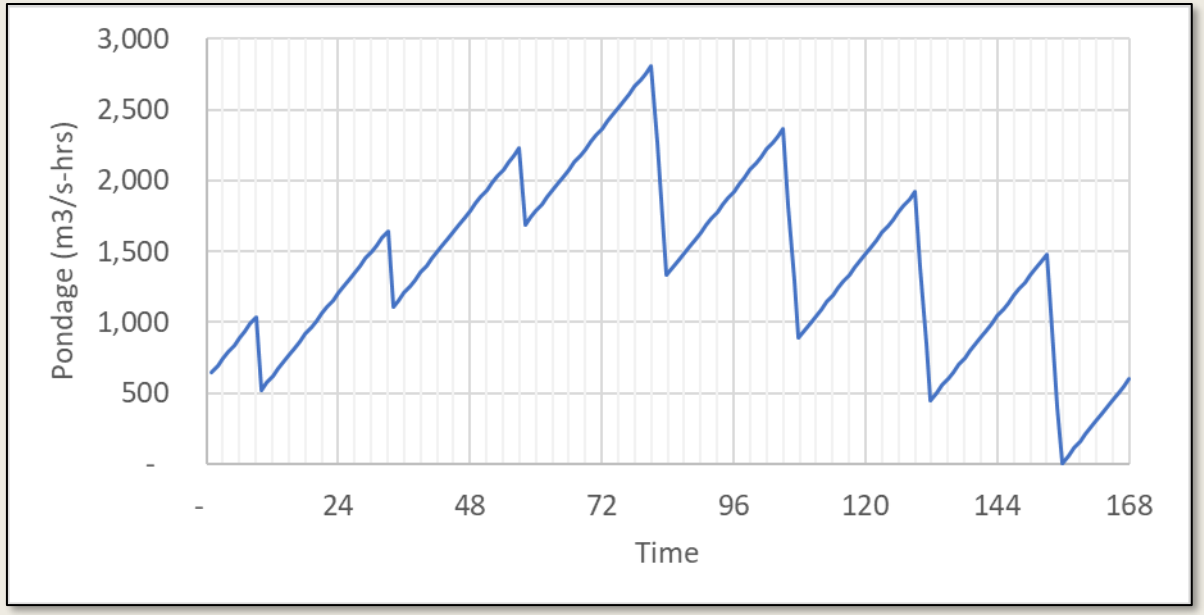
Demand Mass Curves

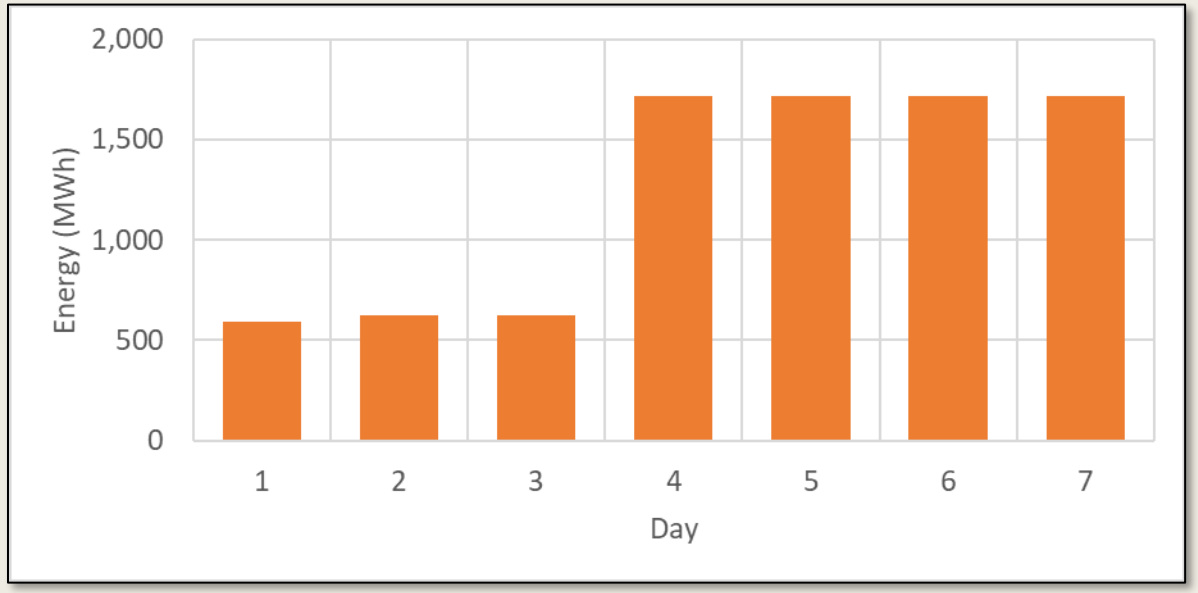


Part VII

Pondage Spreadsheet

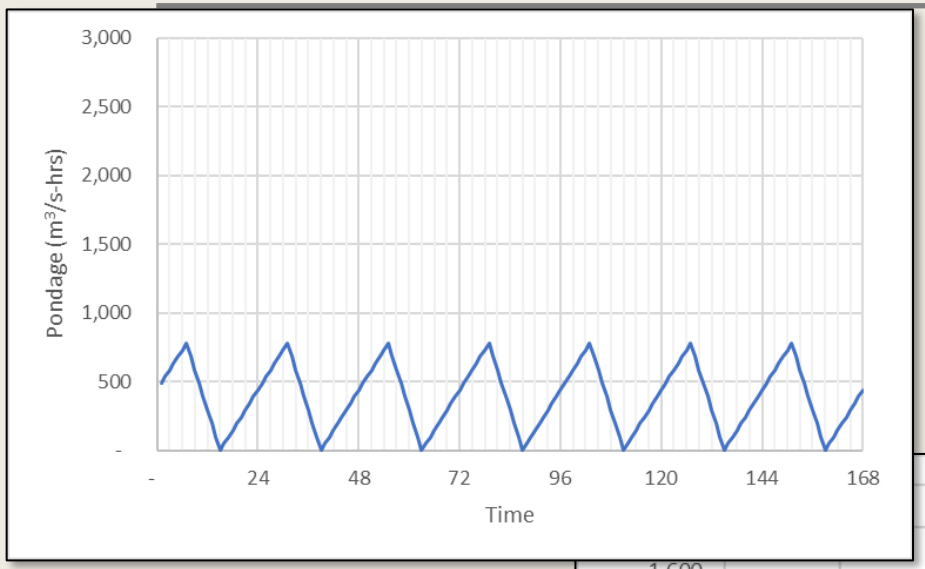
India's Pondage Calculation for Kiru HEP

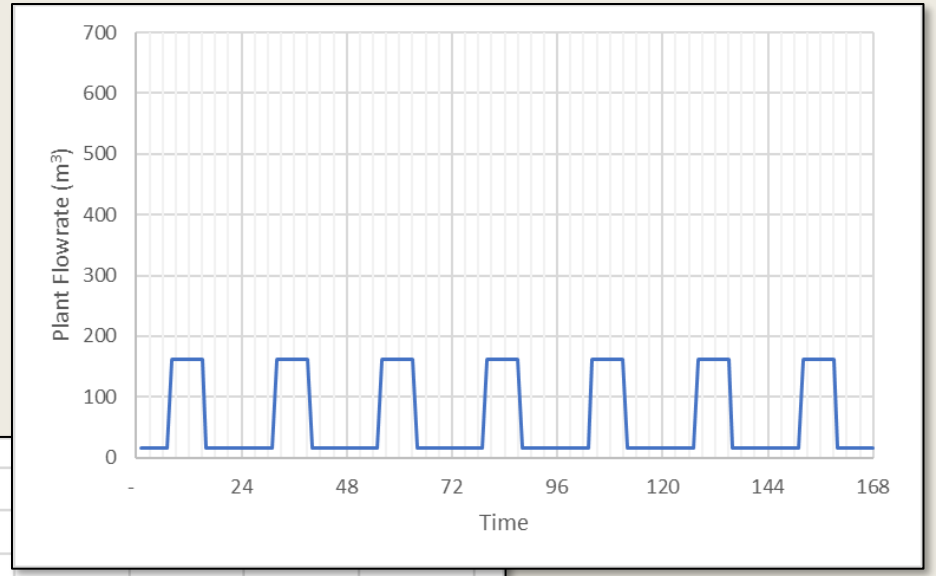


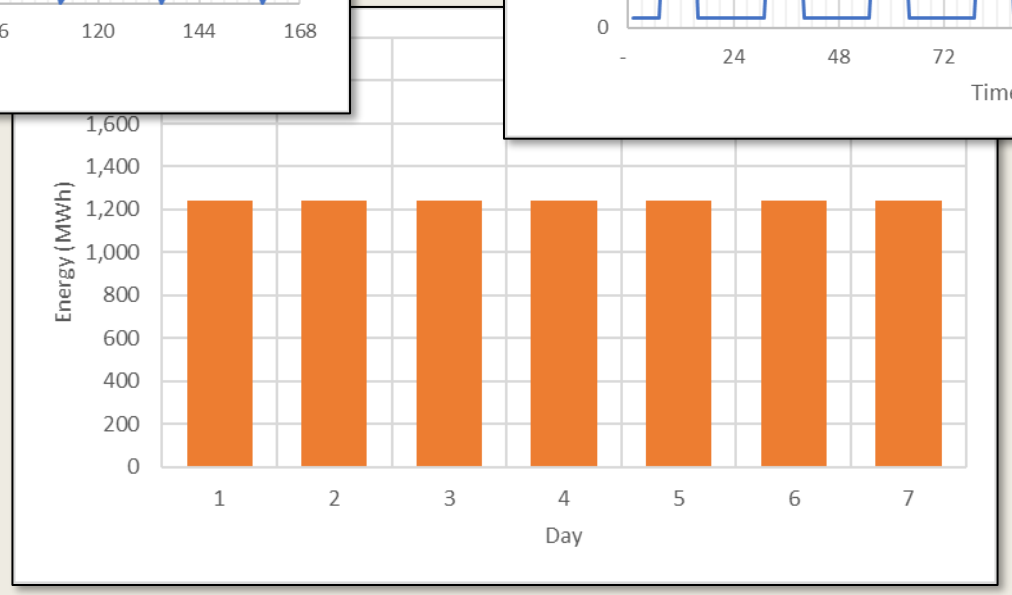


Second Phase Memorial, Appendix E, "COA Excel Table" sheet

Alternative Calculations in Appendix E

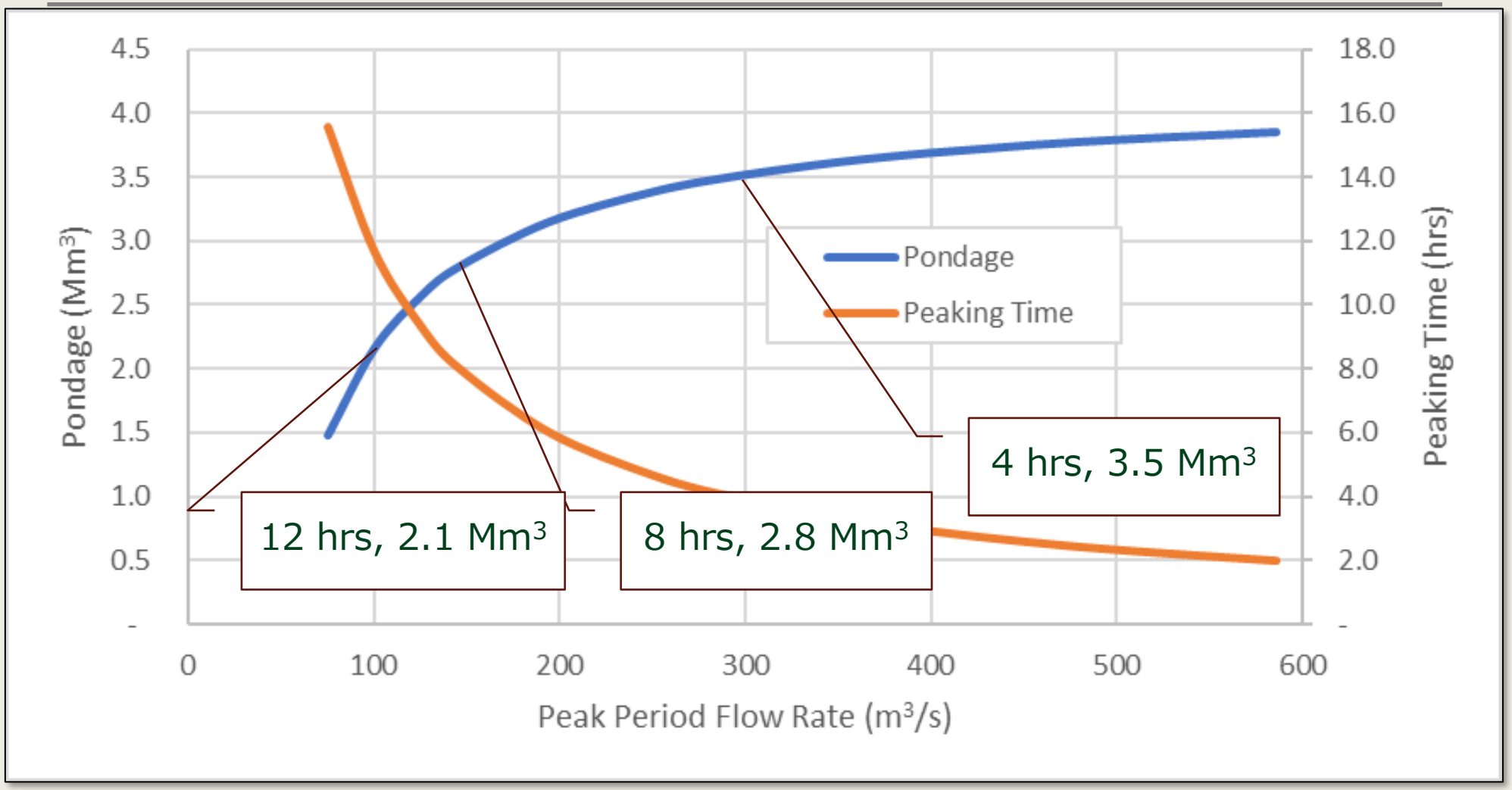






Second Phase Memorial, Appendix E, "Scenario 3" sheet

Pondage with Equal Daily Load Distribution



Second Phase Memorial, Appendix D, Figure 9

Spreadsheet Adjustments

Adjustable Operating Pool Calculations Table

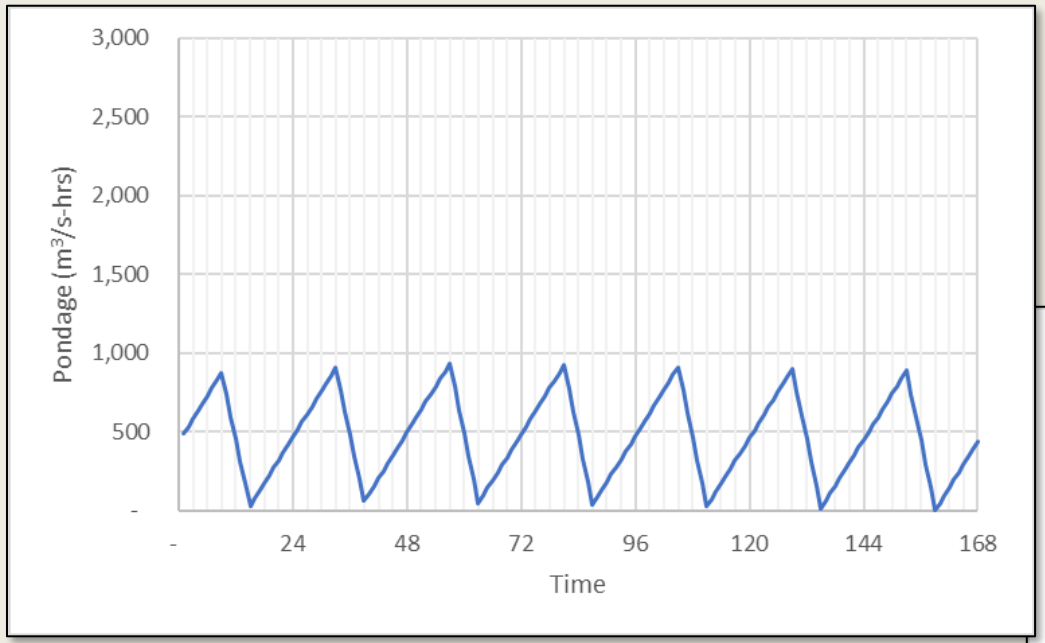
(populated with data and inputs as proposed by India for the Kiru HEP)

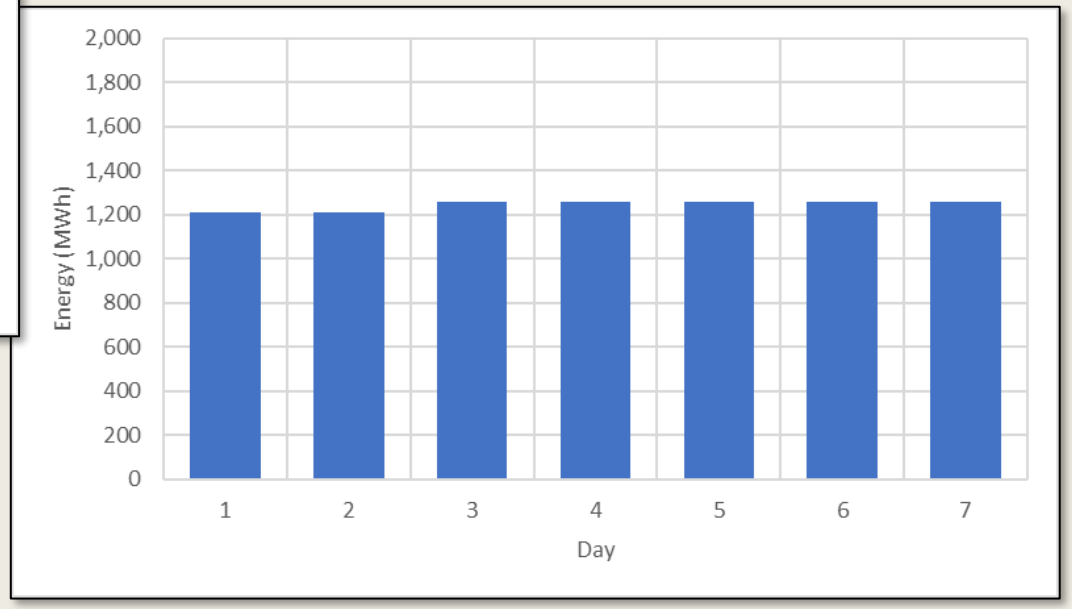
Minimum Mean Discharge (MMD)									=	**65.0**	m^3/s		
Turbine (all 4 units) discharge									=	**586**	m^3/s		
Total Number of Units										**4**			
Outage Units										**1**			
Best Efficiency Discharge/Rated Discharge										**85%**			
Units Available										**0.75**			
Minimum Turbine Flow										**50%**			
										73.25	m^3/s		
Scheduled Peak Period Turbine Discharge										**373.575**	m^3/s		
Minimum Daily Generation Time										**12**	hr		
Maximum Daily Generation Time										**15.9**	hr		
Minimum environmental flow									=	**16.33**	cumec		
									=	2743	cumec-hr (per week)		
Daily inflow = 24 hr X MMD									=	1560	cumec-hr (per day)		
Weekly Peaking Volume									=	8176.56	m^3/s-hrs		
Weekly Eco flow Volume									=	2743.44	m^3/s-hrs		
Minimum outflow to be released in a day=X% daily inflow							**50%**	MIN	=	780	cumec-hr (per day)		
Maximum outflow to be released in a day=X% daily inflow							**130%**	MAX	=	2028	cumec-hr (per day)		
Weekday Energy/Average Energy									=	**101.00%**			
Weekend Energy/Average Energy									=	97.50%			
Head									=	**117.9**	m		
Peak power (assuming X% efficiency) (MW)							**92.2500%**	EFF (n)	=	624.0	MW		

Day	Time				Inflow	*Peaking & Releases	Storage	Cumulative Storage	Power Generation		
	Start Period	End Period	ON/OFF	No. of hrs.	(cumec-hr)	(cumec-hr)	(cumec-hr)	(cumec-hr)	No. of hrs.	Hrs. remaining	MW

Second Phase Memorial, Appendix E, "Scenario 5" sheet

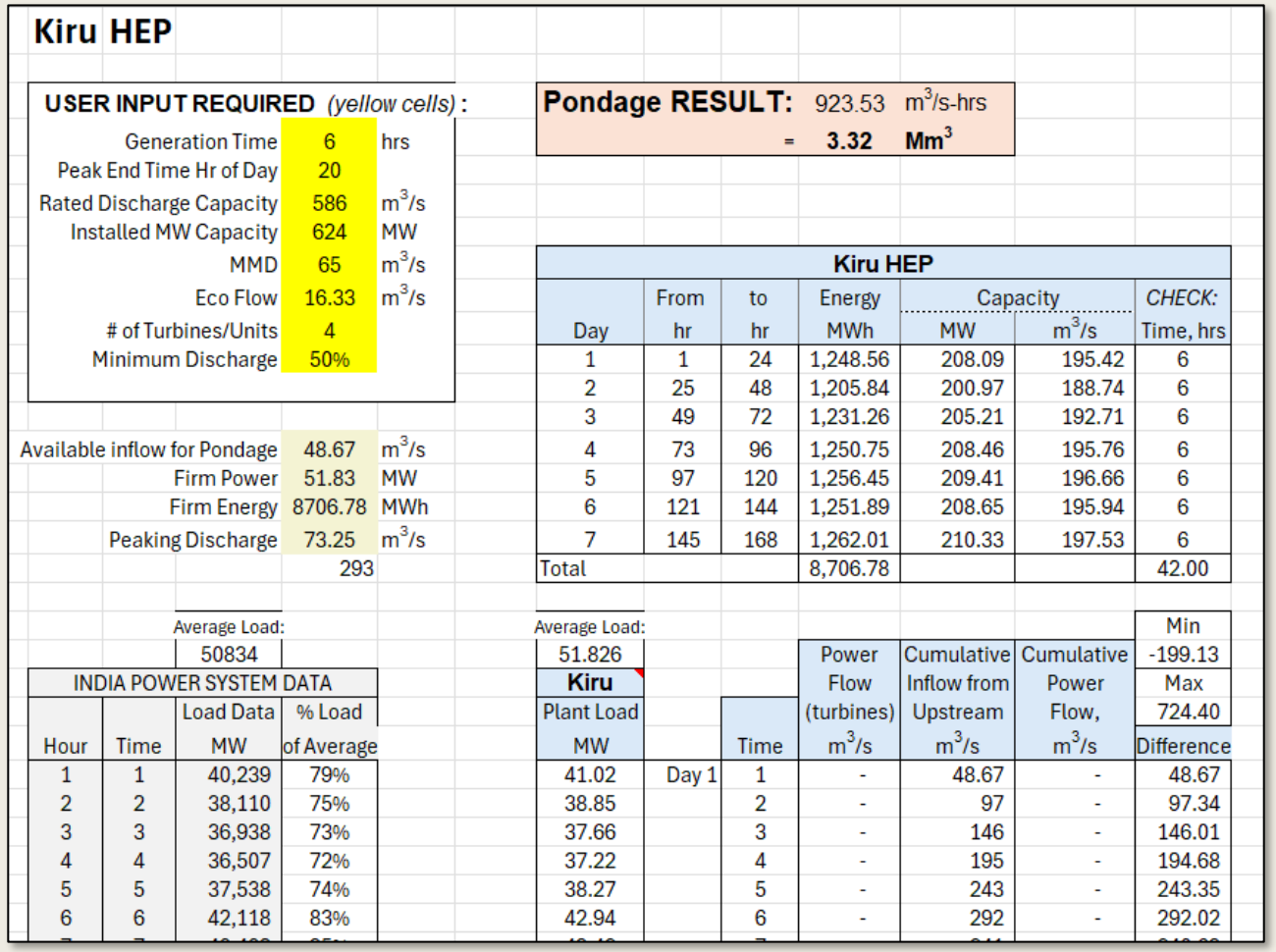
Weekly Pondage Variation and Energy Distribution





Second Phase Memorial, Appendix E, "Scenario 5" sheet

Simplified Pondage Calculation



Kiru HEP

USER INPUT REQUIRED *(yellow cells)* :

Generation Time	6	hrs
Peak End Time Hr of Day	20	
Rated Discharge Capacity	586	m^3/s
Installed MW Capacity	624	MW
MMD	65	m^3/s
Eco Flow	16.33	m^3/s
# of Turbines/Units	4	
Minimum Discharge	50%	

Pondage RESULT: 923.53 m^3/s-hrs = **3.32** **Mm^3**

Available inflow for Pondage	48.67	m^3/s
Firm Power	51.83	MW
Firm Energy	8706.78	MWh
Peaking Discharge	73.25	m^3/s
	293	

Kiru HEP

Day	From hr	to hr	Energy MWh	Capacity MW	Capacity m^3/s	*CHECK:* Time, hrs
1	1	24	1,248.56	208.09	195.42	6
2	25	48	1,205.84	200.97	188.74	6
3	49	72	1,231.26	205.21	192.71	6
4	73	96	1,250.75	208.46	195.76	6
5	97	120	1,256.45	209.41	196.66	6
6	121	144	1,251.89	208.65	195.94	6
7	145	168	1,262.01	210.33	197.53	6
Total			8,706.78			42.00

Average Load: 50834

INDIA POWER SYSTEM DATA

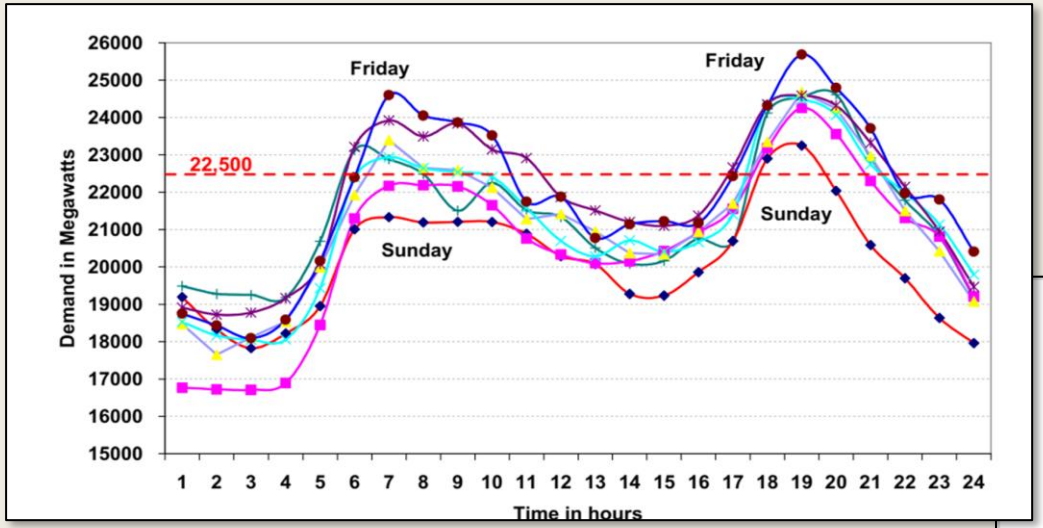
Hour	Time	Load Data MW	% Load of Average
1	1	40,239	79%
2	2	38,110	75%
3	3	36,938	73%
4	4	36,507	72%
5	5	37,538	74%
6	6	42,118	83%

Average Load: 51.826

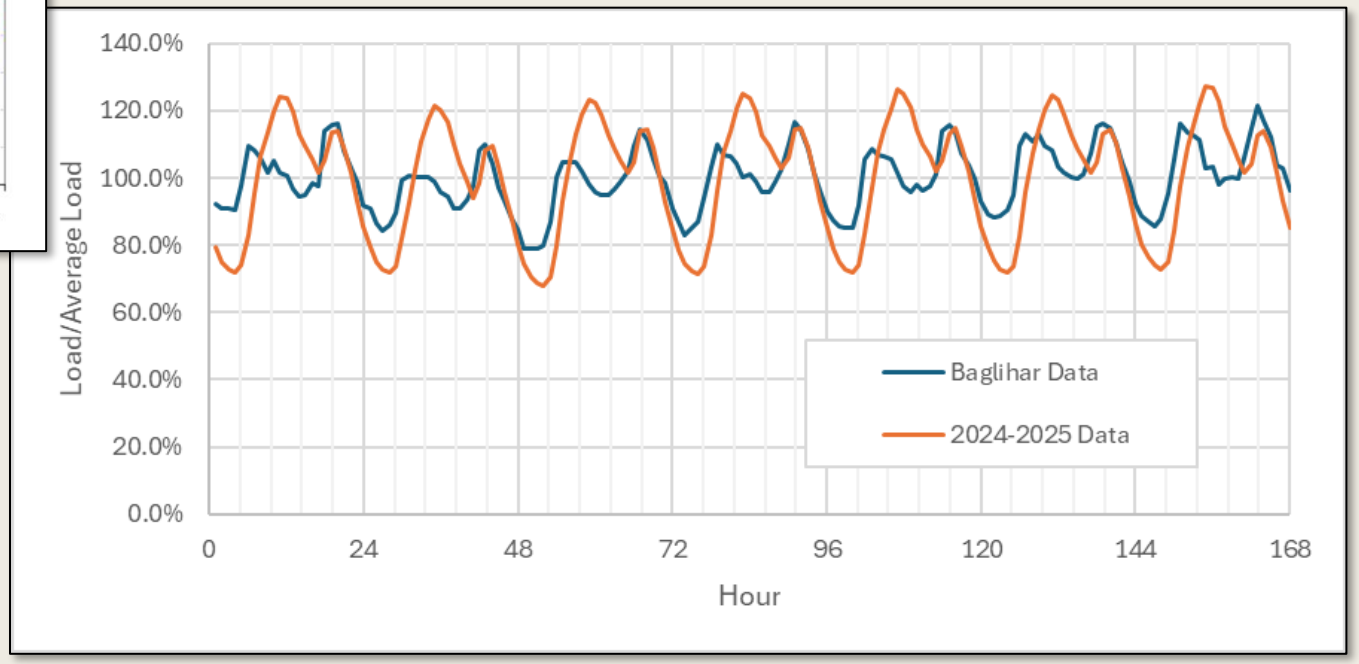
Kiru

		Plant Load MW	Time	Power Flow (turbines) m^3/s	Cumulative Inflow from Upstream m^3/s	Cumulative Power Flow, m^3/s	Min -199.13 / Max 724.40 / Difference
							Min -199.13
							Max 724.40
Day 1	1	41.02	1	-	48.67	-	48.67
	2	38.85	2	-	97	-	97.34
	3	37.66	3	-	146	-	146.01
	4	37.22	4	-	195	-	194.68
	5	38.27	5	-	243	-	243.35
	6	42.94	6	-	292	-	292.02

Baglihar Load



Baglihar Determination, Annex 6, p. 17 (Daily Load Curves in Northern Region, December 2004, **P-0547/BR-0005**)



Part VIII

Summary

Summary of Inputs

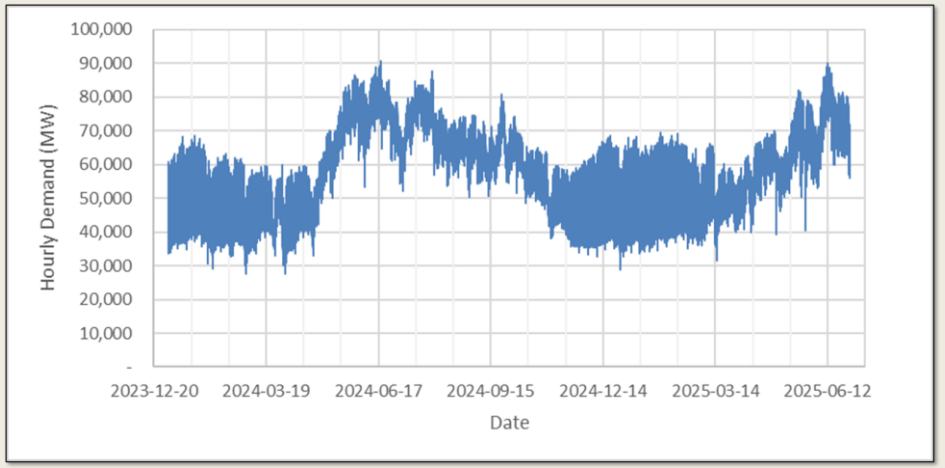
Minimum Mean Discharge (m^3/s)

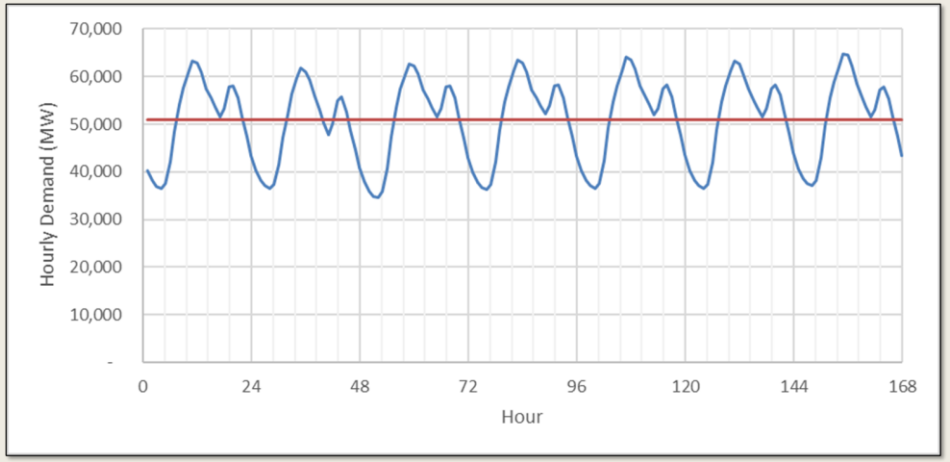
Load of the power system

Plant characteristics

- Capacity (MW)
- Rated Discharge (m^3/s)
- Minimum Discharge (m^3/s)
- Head, efficiency, etc.
- Eflow

Dispatch





Summary of Calculation

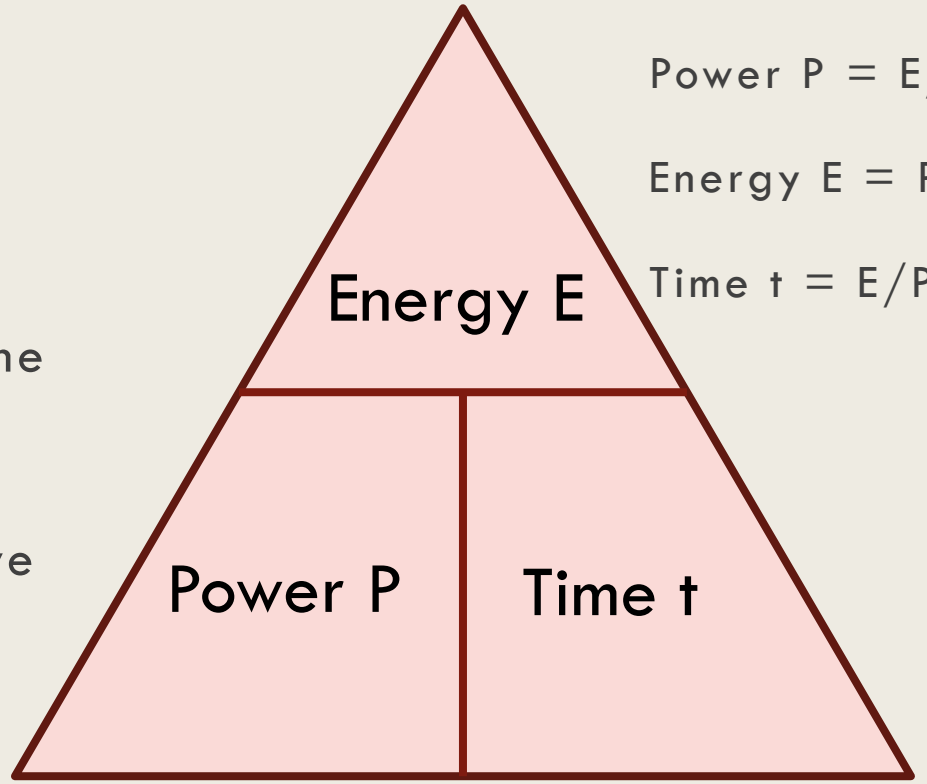
Pondage based on MMD less Eflow

Select daily dispatch duration

Define daily variation in energy

Compute Power available daily for turbine limits

Compute weekly Pondage from mass curve



Power P = E/t

Energy E = P x t

Time t = E/P

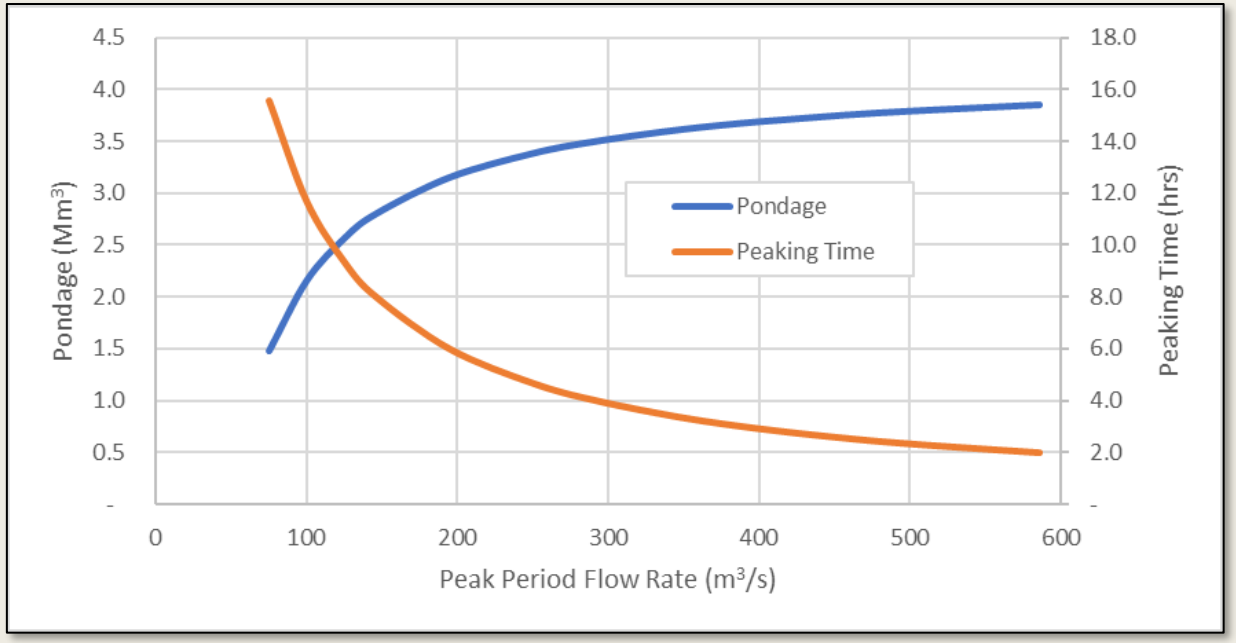
Summary of Pondage Outputs

Daily Pondage

- Depends on peaking duration and MMD

Weekly Pondage

- Depends on daily energy demand
- Compute combined daily peaking duration/capacity to generate available energy
- Compute Weekly mass curve to estimate Pondage



$$V_P = \left(24(Q - Q_e) - \frac{(24)(Q - Q_e)^2}{Q_P}\right) \times 0.0036$$

Conclusions

- Pondage computed for the MMD and the characteristics of a Plant.
- Power system load provides the weekly variation in the load, and the distribution of the MMD volume through the week.
- A daily dispatch pattern is determined for water or energy allocated to each day within the seven days.
- The daily dispatch pattern can be made according to reasonable limits for the duration of operation. Cannot exceed Paragraph 15 limits.
- Capacity used for the daily operation will depend on the energy allocated for each day and the duration of the operation.
- The Pondage required for the week depends on the variation of energy through the week and the daily dispatch pattern for the Plant.


ایمان اتحاد نظم