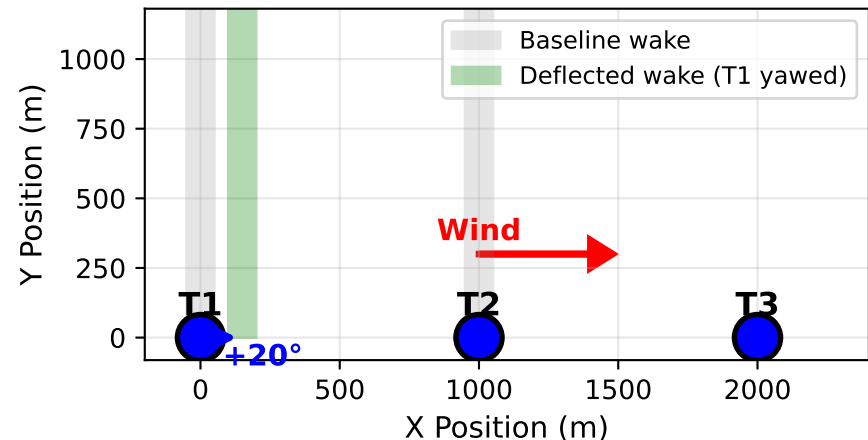
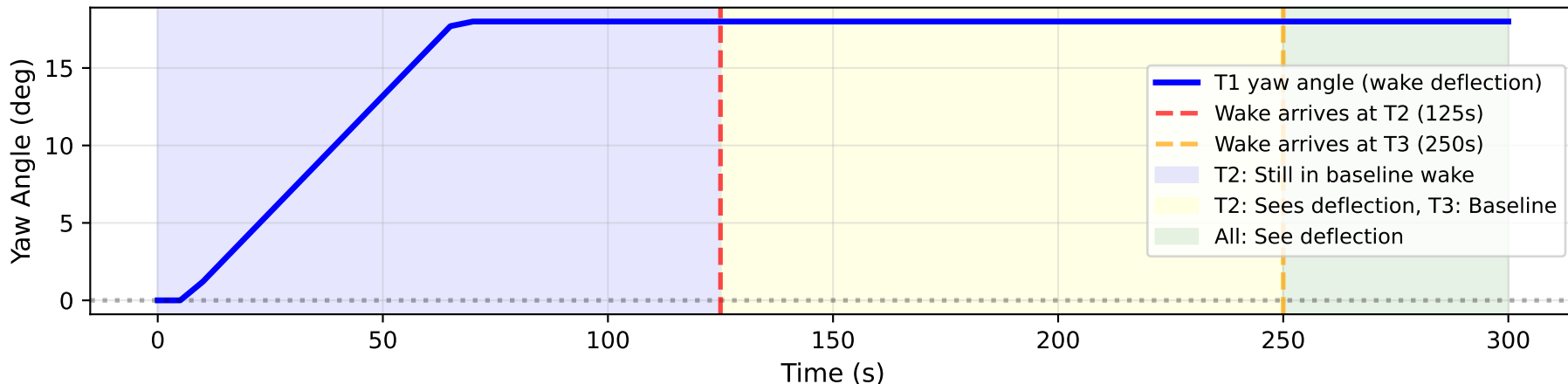


Wake Advection Dynamics: Time Delays & Power Gains from Wake Steering

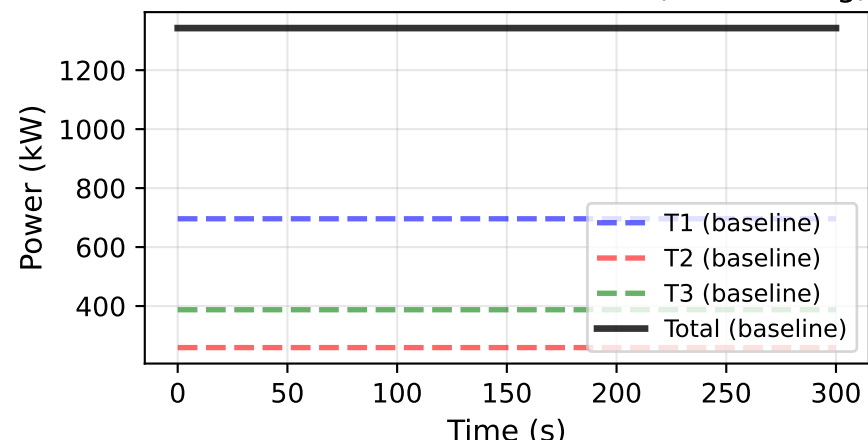
Farm Layout: Wake Steering Effect



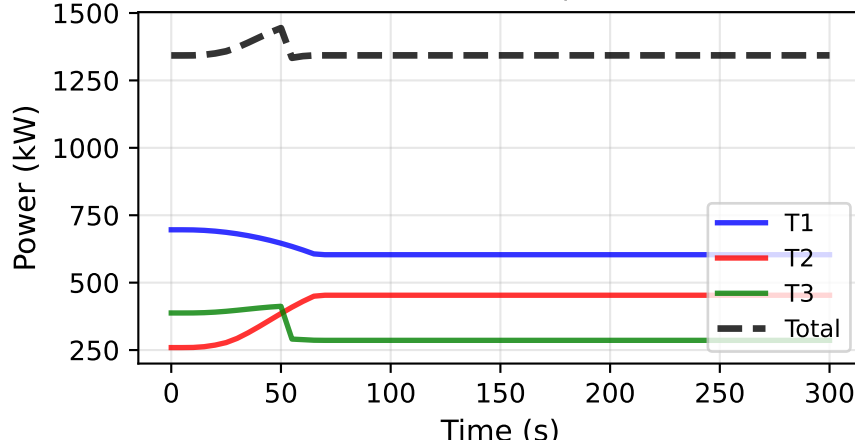
T1 Yaw Change Timeline: Wake Deflection Propagation



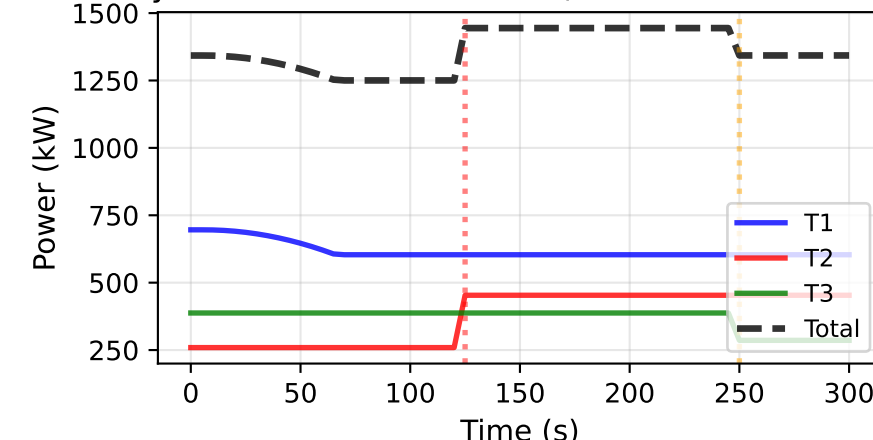
Baseline: All Turbines at 0° Yaw (No Steering)



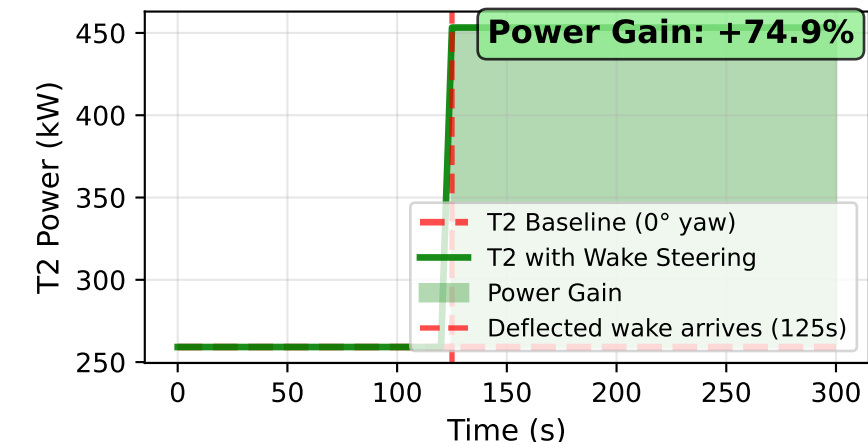
Instant Wake: T1 Yaws +20° (WRONG - No Delays)



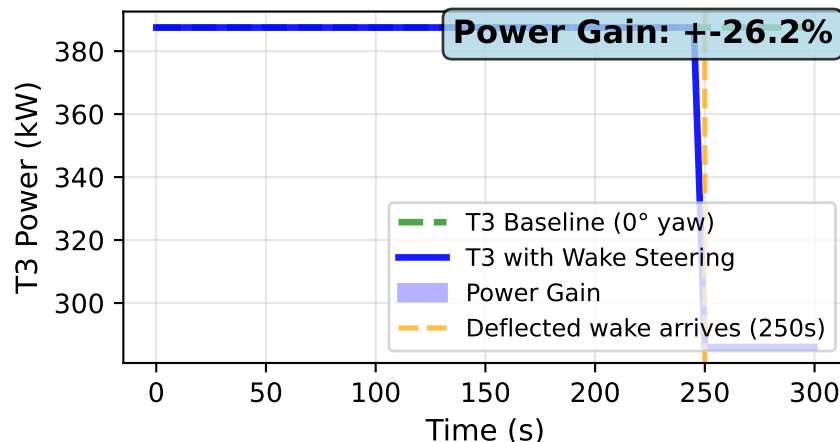
Delayed Wake: T1 Yaws +20° (CORRECT - With Delays)



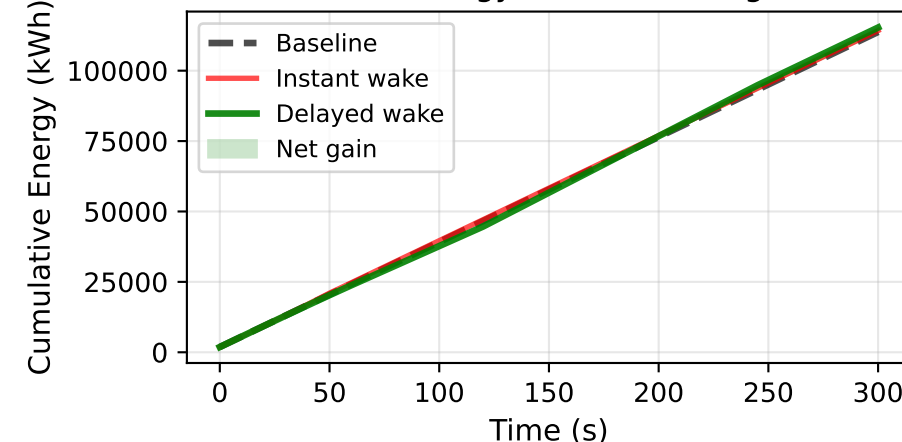
T2 Power Increase from Wake Deflection



T3 Power Increase from Wake Deflection



Cumulative Energy: Wake Steering Benefit



WAKE ADVECTION & STEERING SUMMARY

FARM SETUP

- 3 turbines in line
- Spacing: 1000 m
- Wind speed: 8.0 m/s

WAKE DELAYS

- T1 → T2: 125 s
- T1 → T3: 250 s
- Advection speed: 8.0 m/s

POWER GAINS FROM WAKE STEERING

- T2 power gain: + 74.9%
- T3 power gain: +-26.2%
- Total farm gain: + 1.4%

KEY INSIGHTS:

- WAKE STEERING WORKS: When T1 yaws +20°, it deflects its wake AWAY from downstream turbines → increased power
- DELAYS MATTER: Downstream turbines don't feel the benefit instantly - wake takes 125-250s to propagate
- MPC MUST ACCOUNT FOR DELAYS: Ignoring advection dynamics leads to 0.9% modeling error in energy prediction
- ACTION HORIZON SIZING: t_{AH} must be $\geq 250s$ (max delay) to capture full wake propagation effects

WHY THIS VALIDATES OUR MPC FORMULATION:

- ✓ Time-shifted cost function correctly accounts for wake propagation delays
- ✓ Action horizon $t_{AH} = 100s > 250s$ (maximum delay in system)
- ✓ Prediction horizon $T_{opt} = 400s$ captures full transient response
- ✓ Delay loop in trajectory simulation ensures physical realism