To 33% and Beyond:

Grid Integration Challenges for Renewable Generation

presented to:

UCLA Smart Grid Thought Leadership Forum
March 28, 2012

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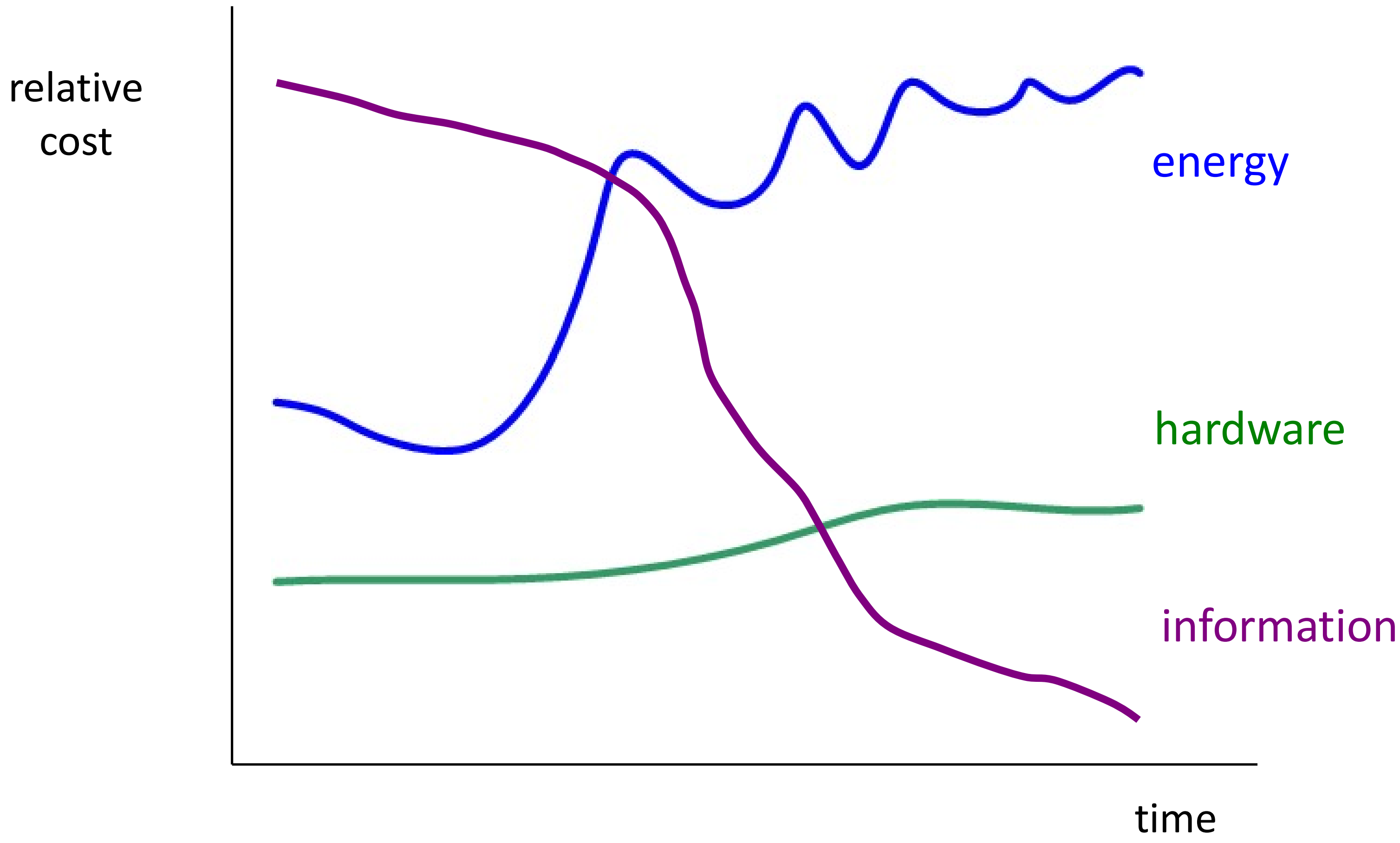
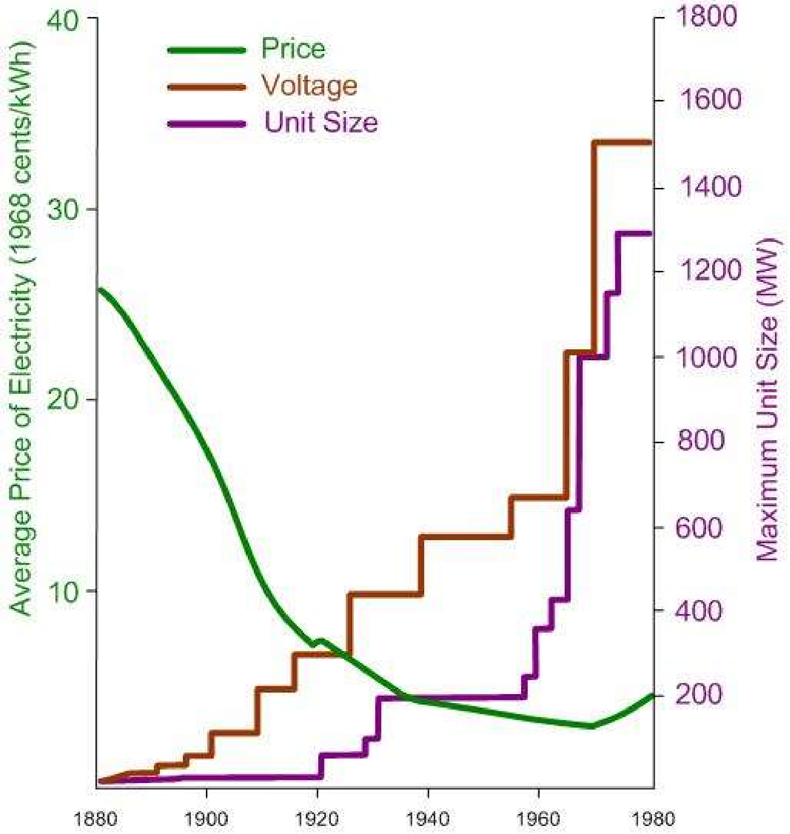
Disclaimer

This presentation is based in part on work sponsored by the California Energy Commission, but does not necessarily represent the views of, nor has it been approved or disapproved by, the Energy Commission.

The author gratefully acknowledges support from the Public Interest Energy Research program.


relative
cost
energy
hardware
information
time

Historical drivers toward "smart grid" development



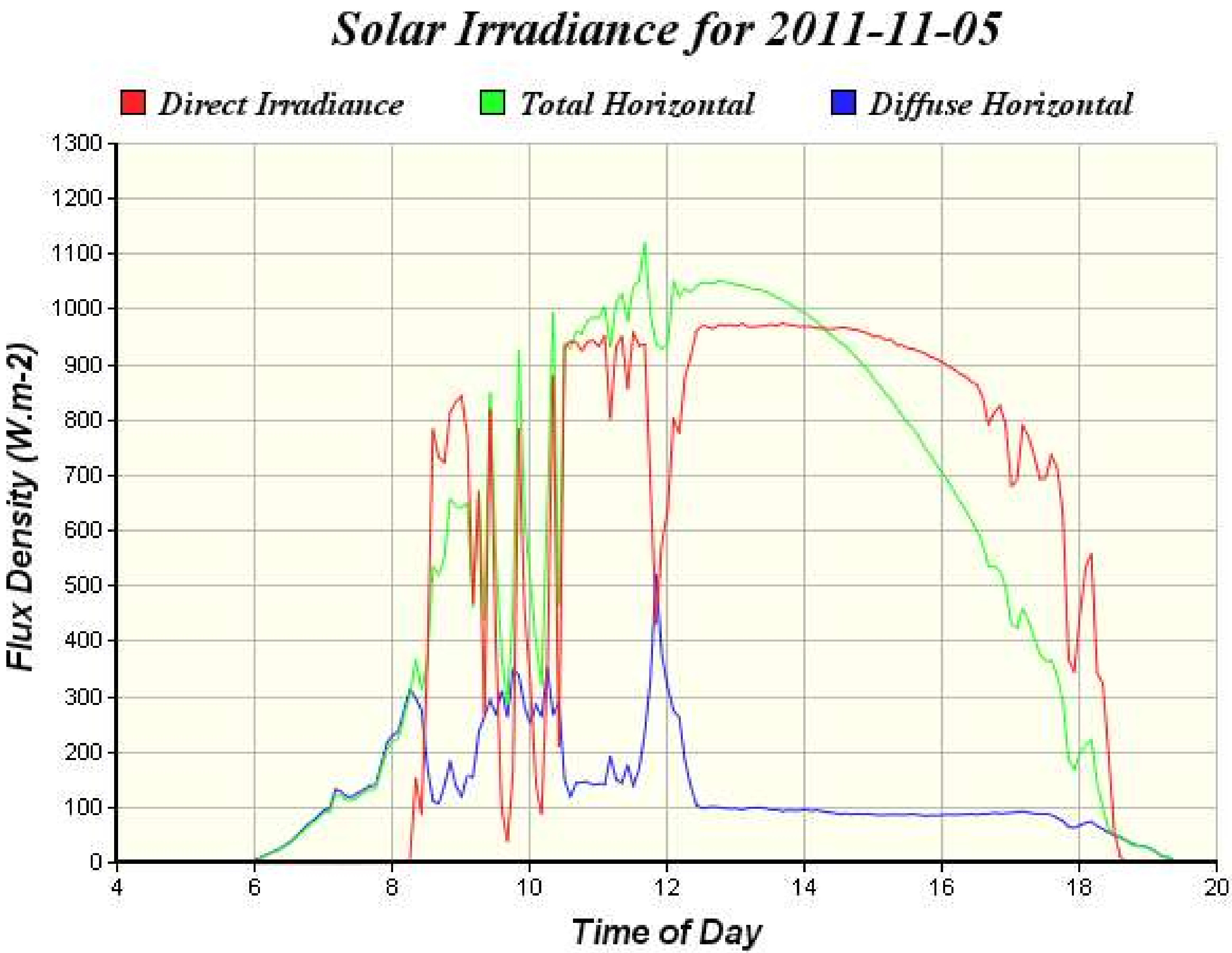
Adapted from Economic Regulatory Administration, 1981

- limited economies of scale
- oil prices
- high interest rates in 1970s and '80s hampering large, inflexible units
- recognition of environmental costs
- PURPA: diversity of generators
- declining transmission investment
- increasing dependence on long-distance connectivity: vulnerability
- electronic loads: reliability needs, modeling challenge
- competitive market philosophy

The grid is becoming harder to operate.

Meanwhile, we want electricity that's clean, green, good-looking, reliable…

and cheaper, too!



Solar Irradiance for 2011-11-05
Direct Irradiance
Total Horizontal
Diffuse Horizontal
Flux Density (W.m-2)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
4
6
8
10
12
14
16
18
20
Time of Day

This graph shows the aggregated output from the wind generation connected directly to the California ISO Balancing Area.


Herding Cats
1
2
3
4
5
6
7
It CAN be done
ICANHASCHEEZBURGER.COM

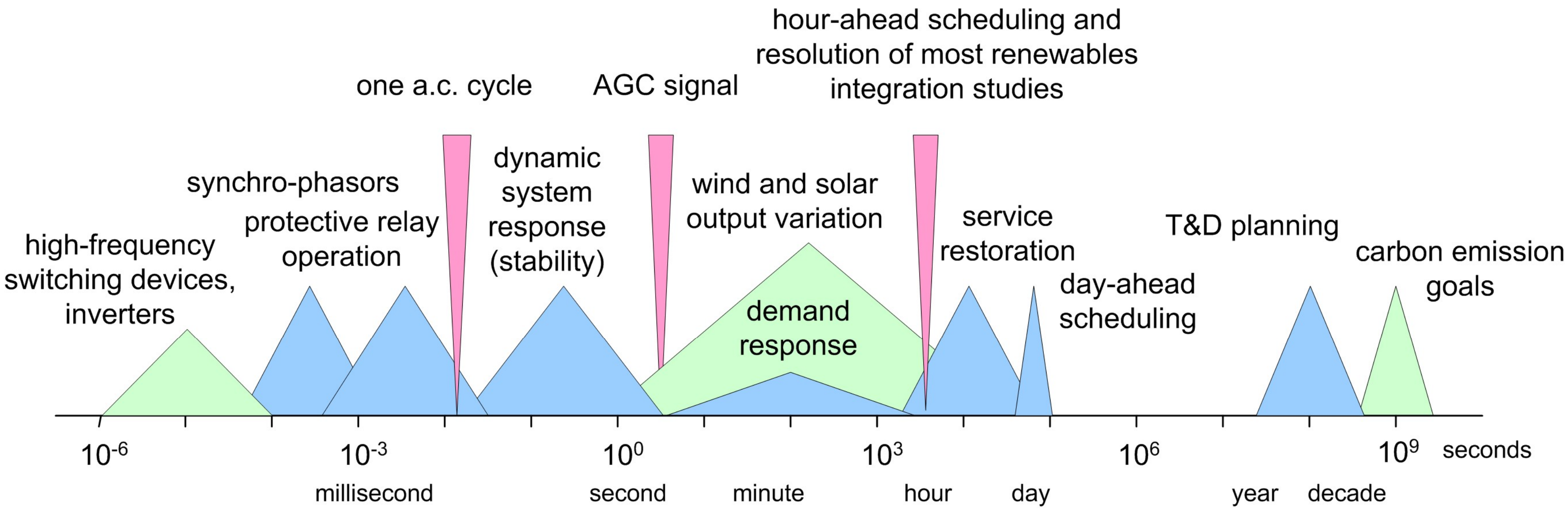
Problems are difficult but solvable

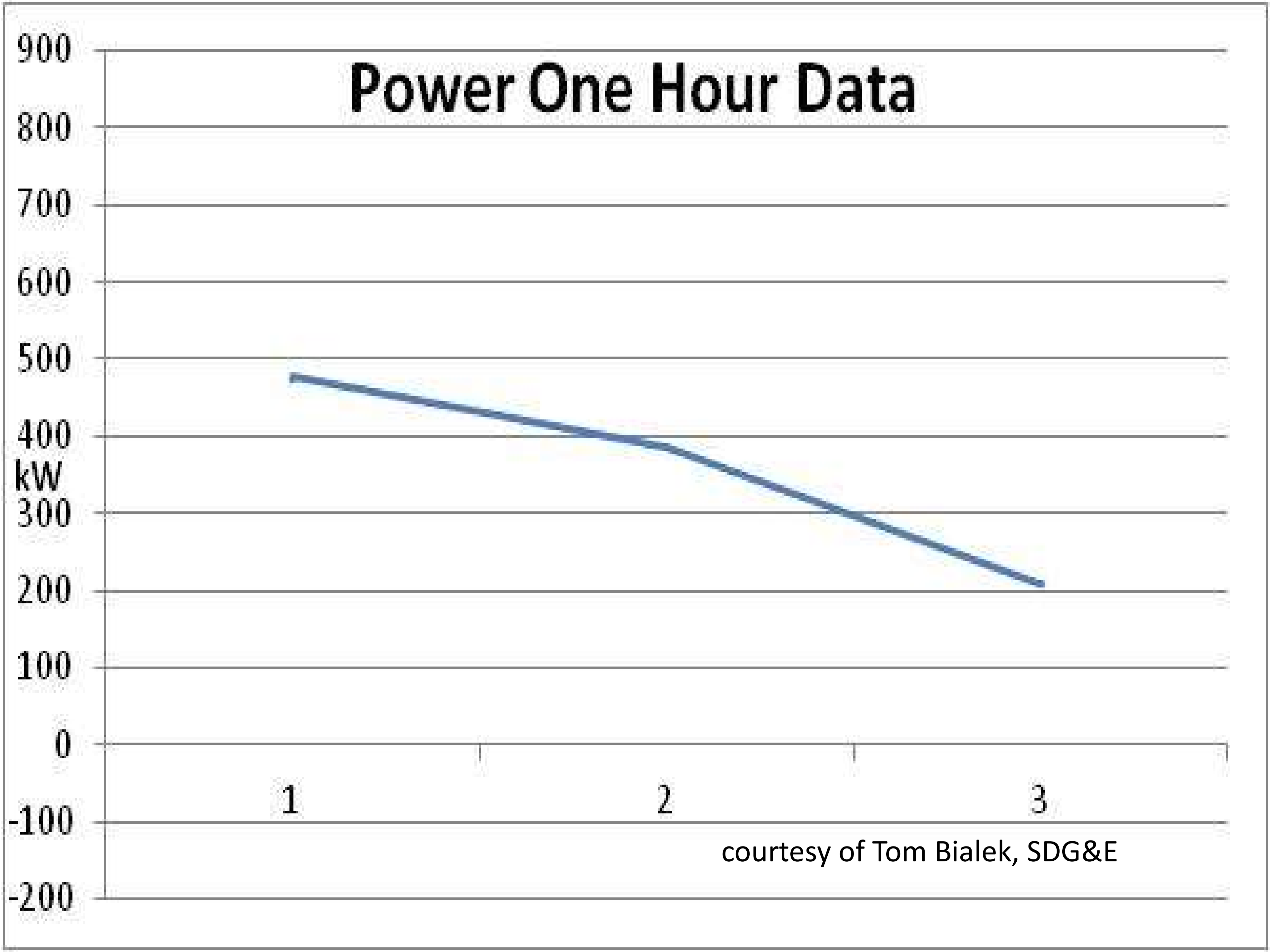
33% by 2020 in CA

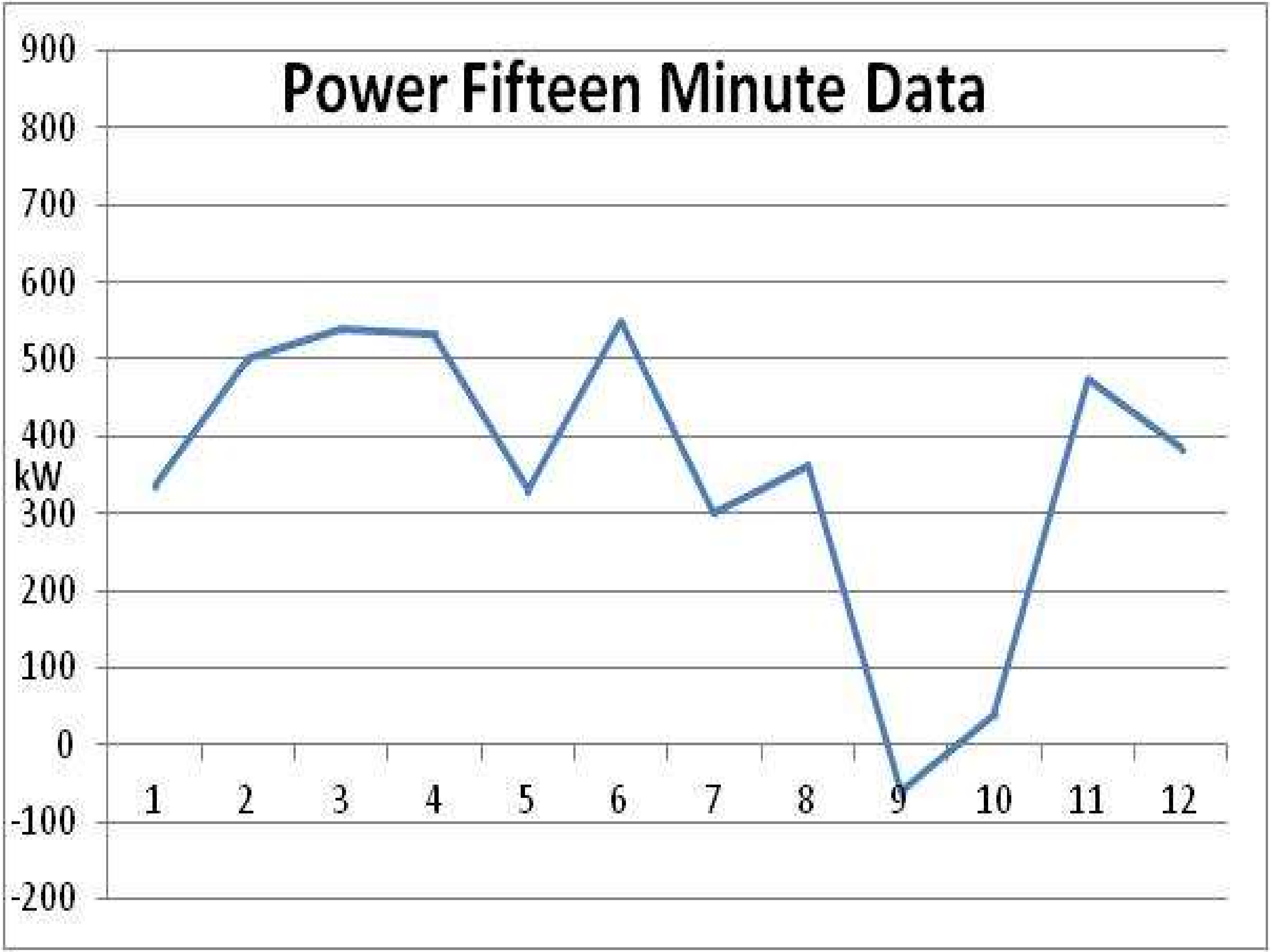
12,000 MW in distributed installations

➡ **100% ?**

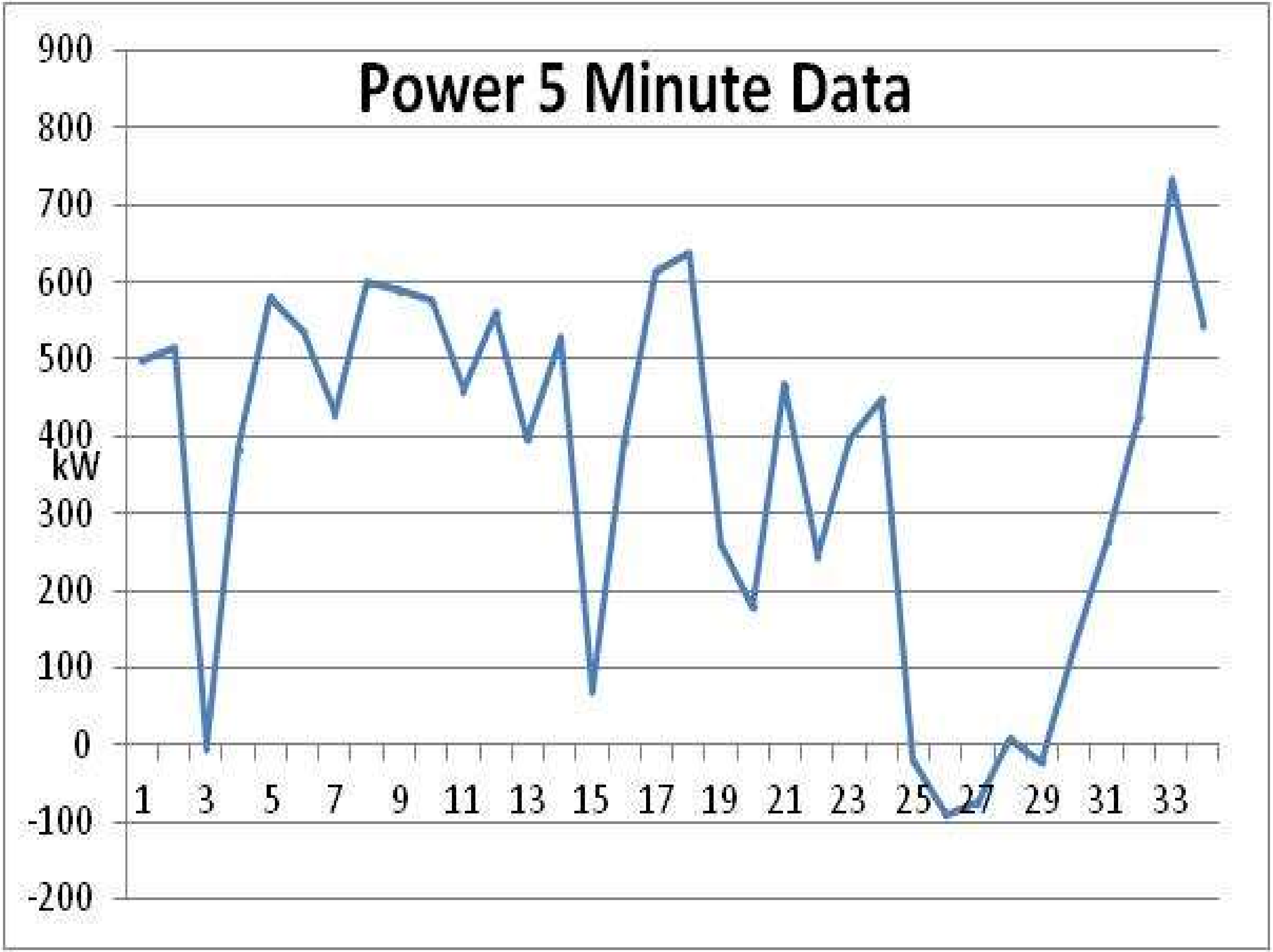
Time scales in electric grid operation



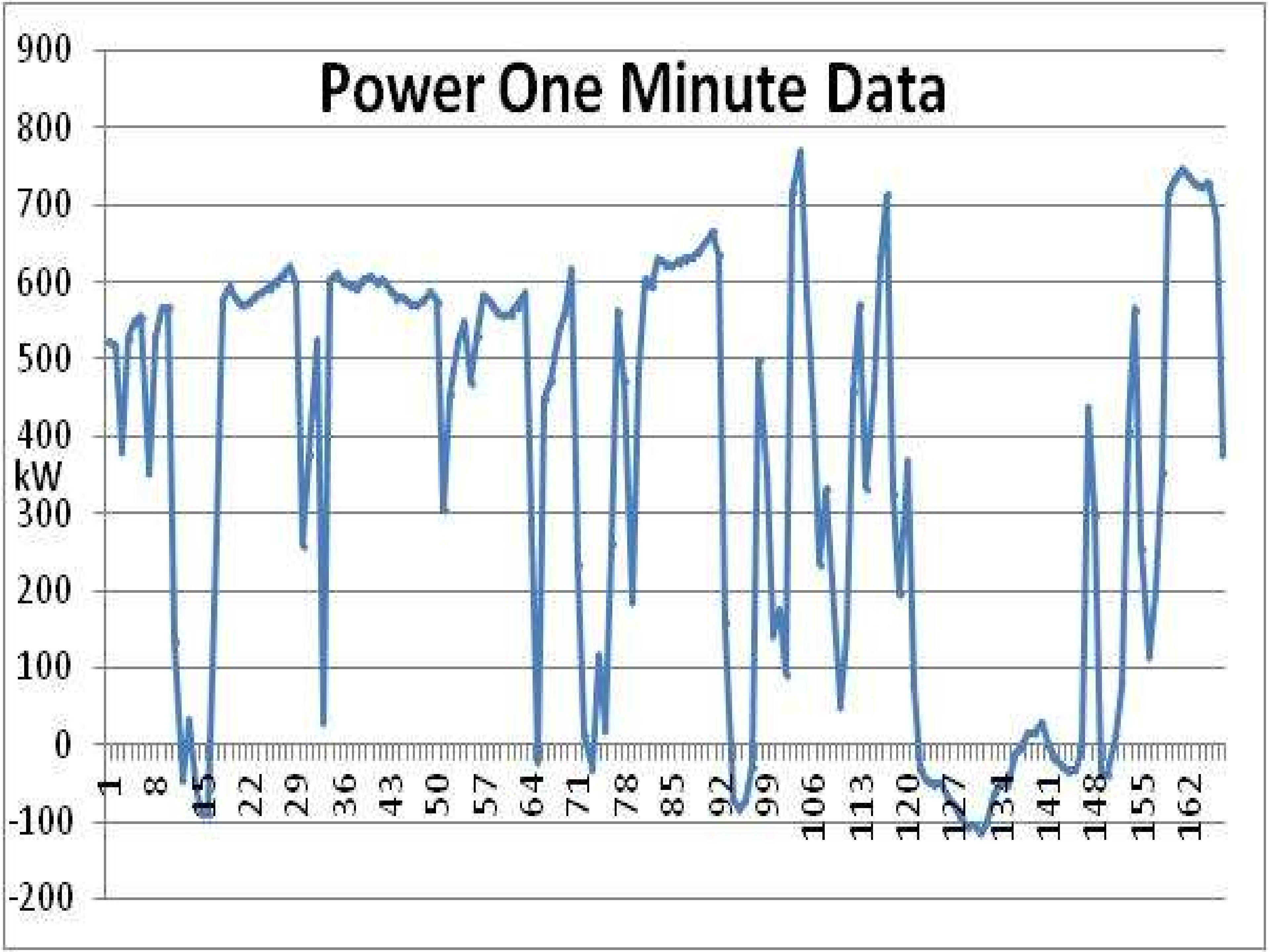

Power One Hour Data
900
800
700
600
500
400
kW
300
200
100
0
-100
-200
1
2
3
courtesy of Tom Bialek, SDG&E



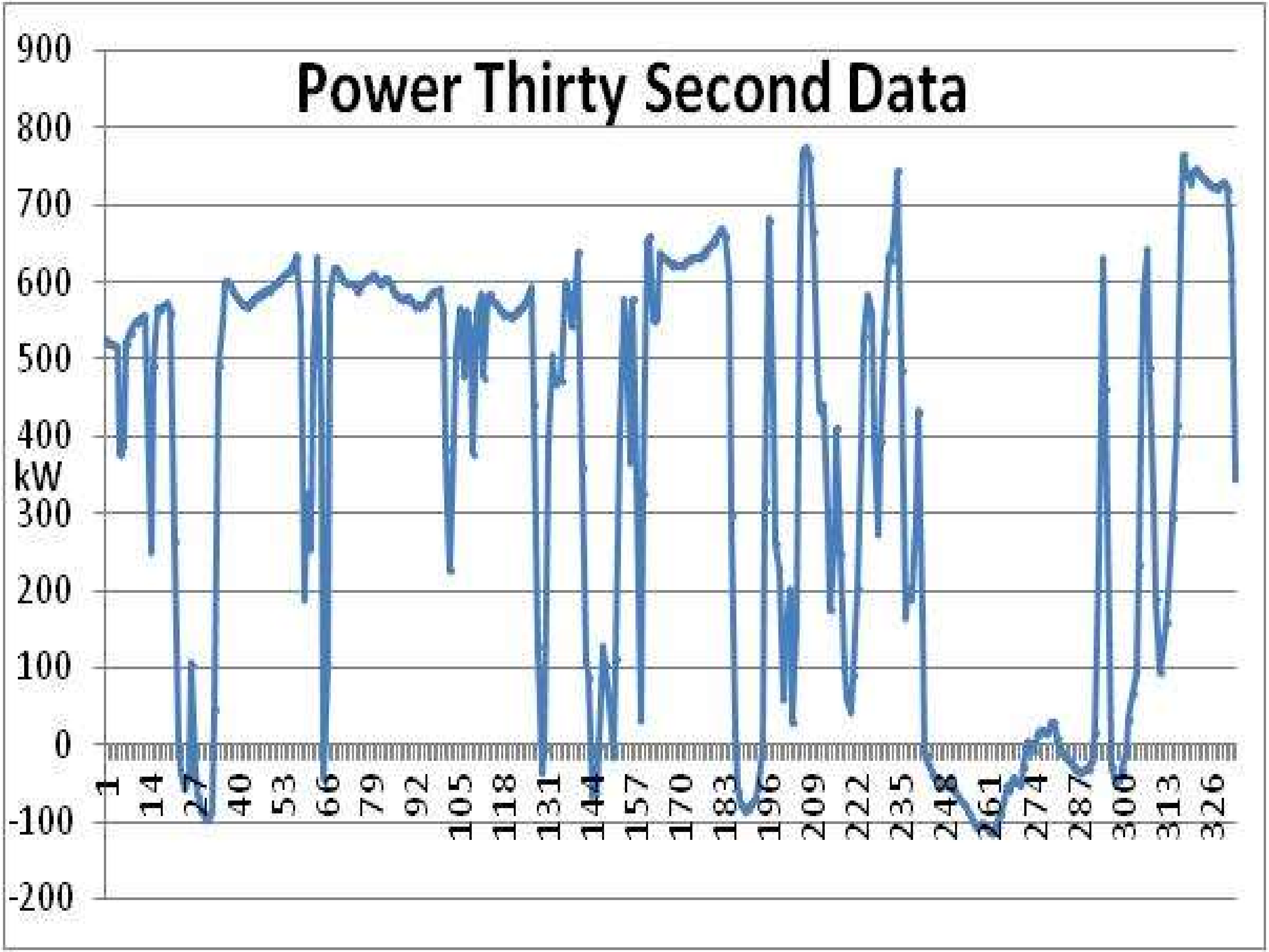
Power Fifteen Minute Data
900
800
700
600
500
400
kW
300
200
100
0
-100
-200
1
2
3
4
5
6
7
8
9
10
11
12



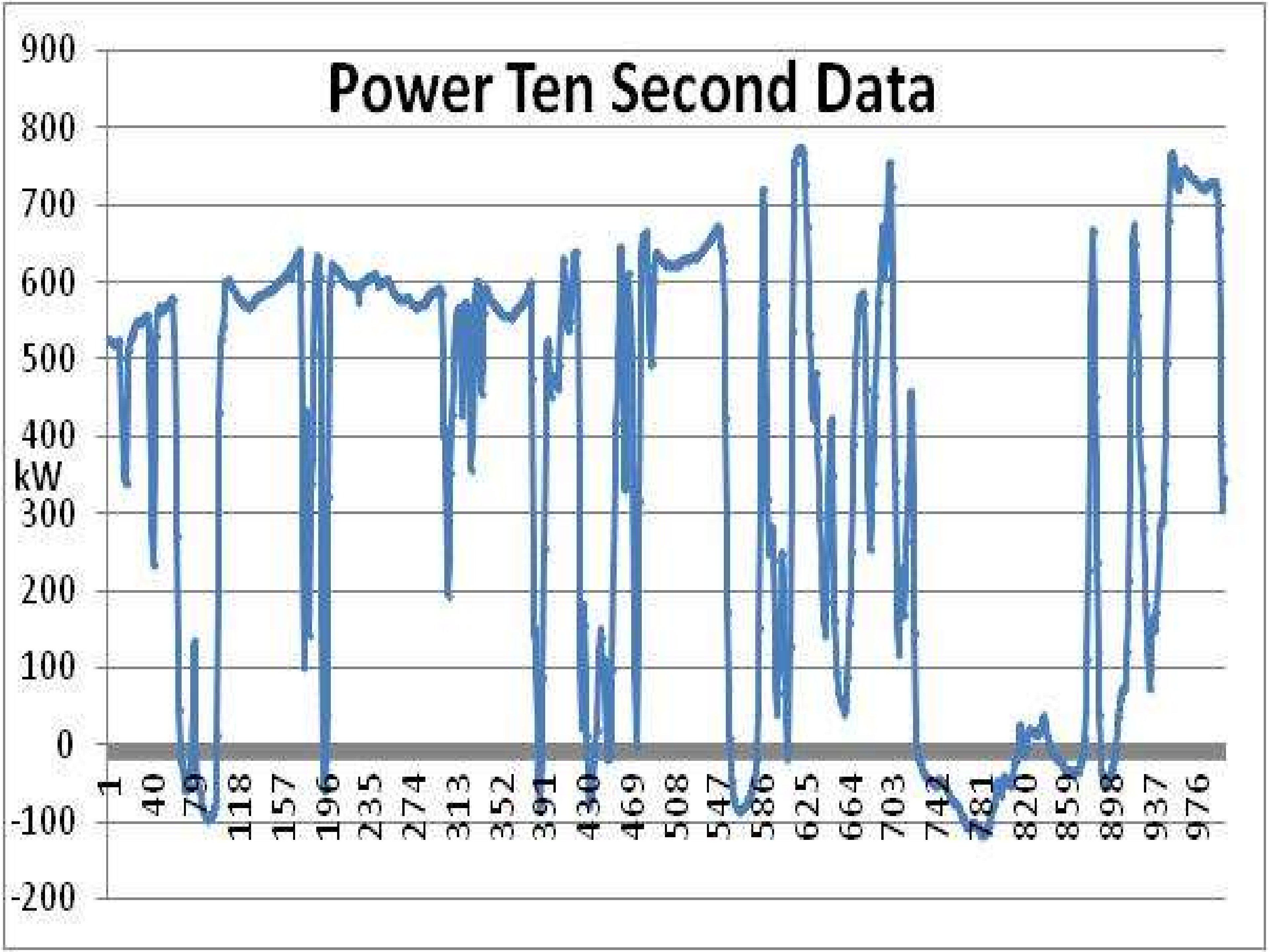
Power 5 Minute Data
kW
900
800
700
600
500
400
300
200
100
0
-100
-200
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33

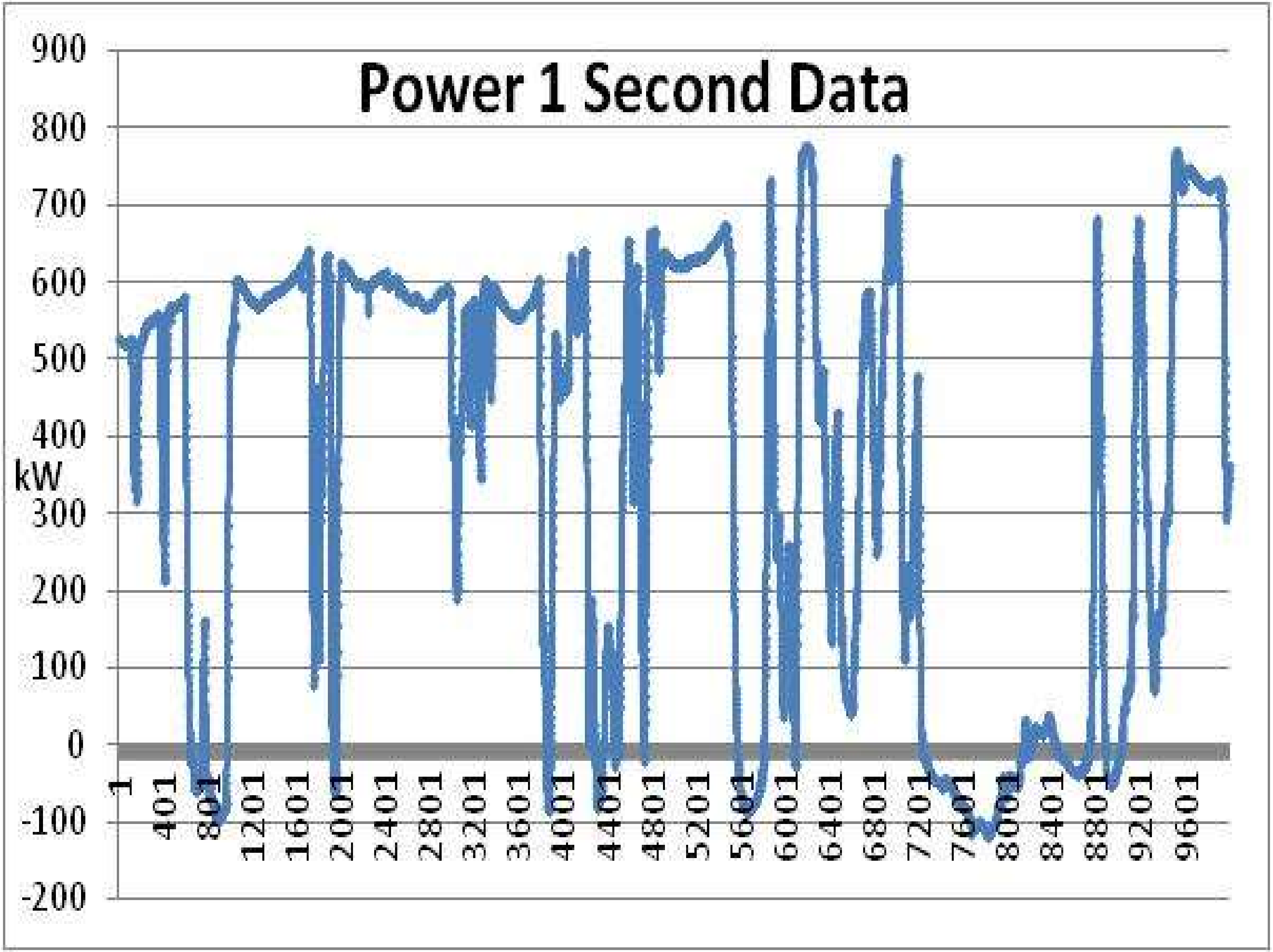


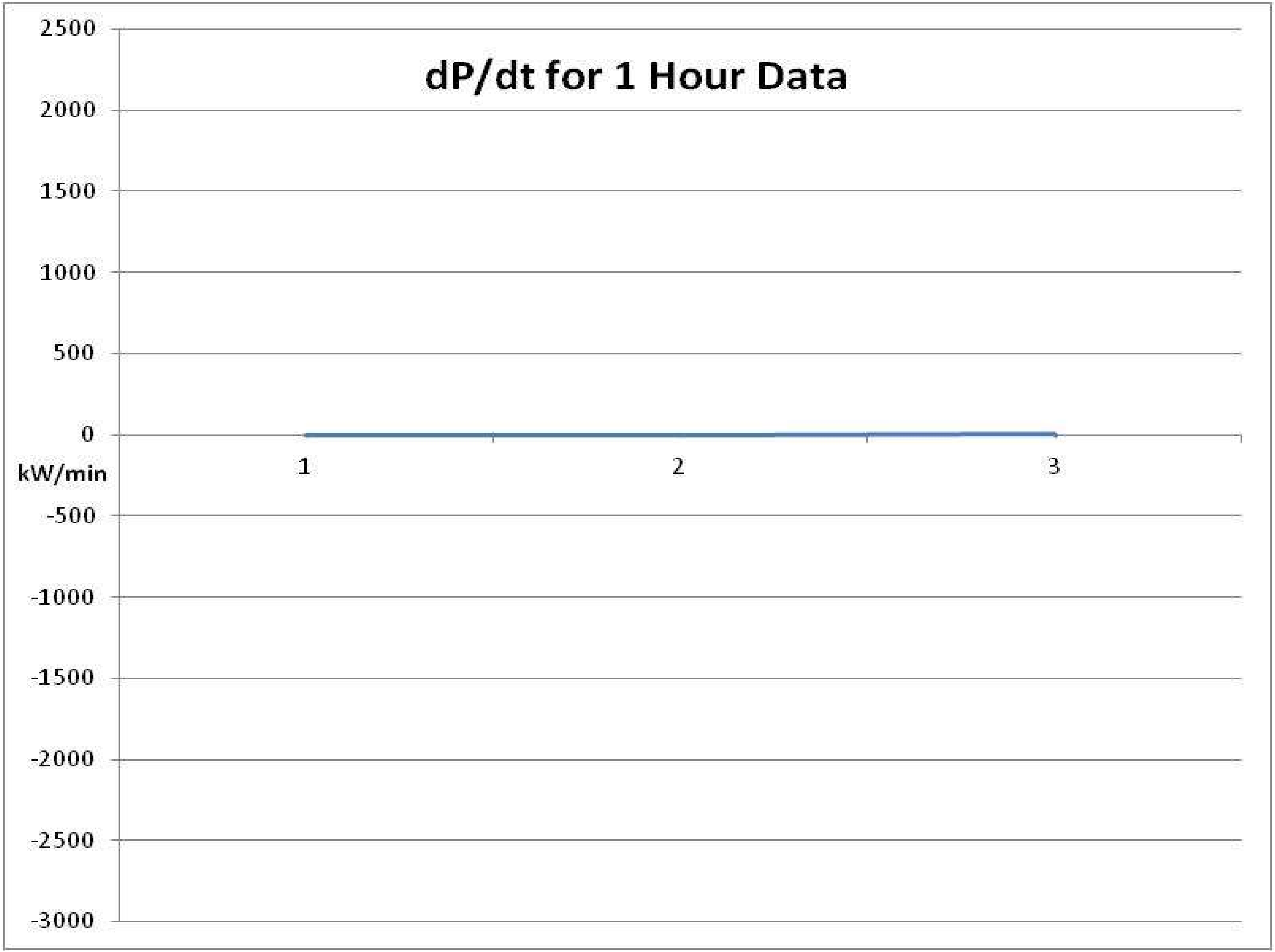
Power One Minute Data
kW
900
800
700
600
500
400
300
200
100
0
-100
-200
1
8
15
22
29
36
43
50
57
64
71
78
85
92
99
106
113
120
127
134
141
148
155
162

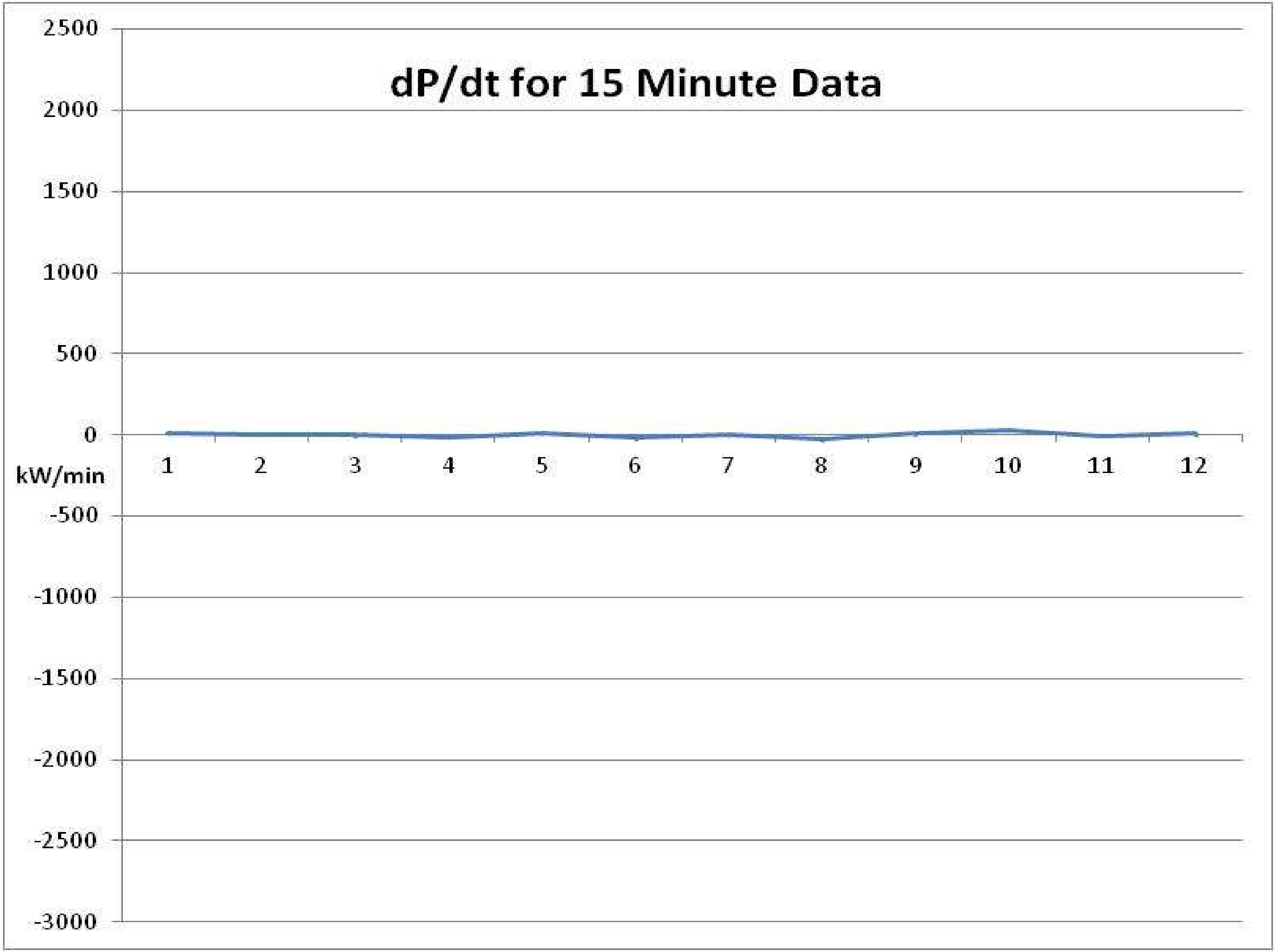


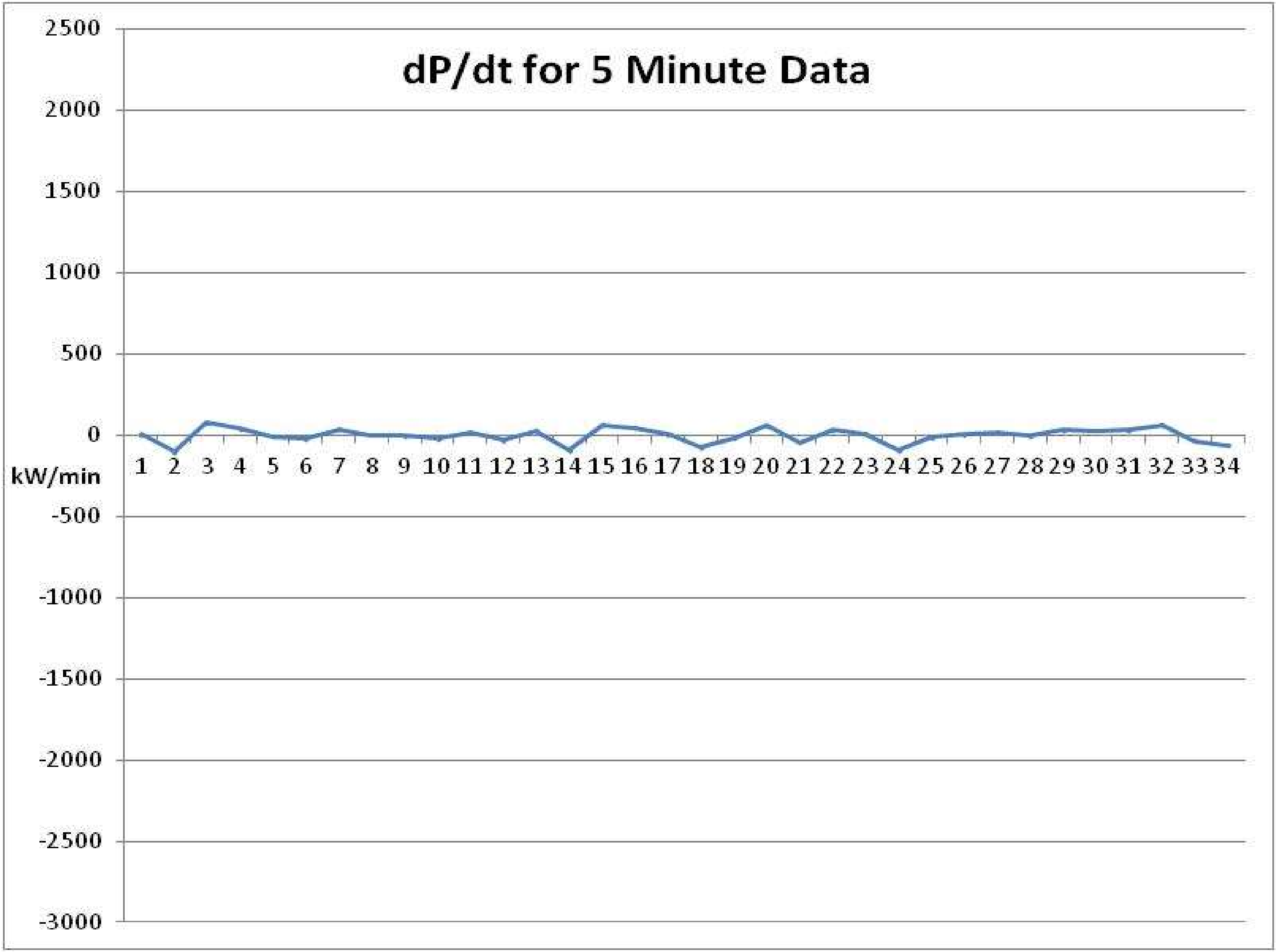
Power Thirty Second Data
kW
900
800
700
600
500
400
300
200
100
0
-100
-200
1
14
27
40
53
66
79
92
105
118
131
144
157
170
183
196
209
222
235
248
261
274
287
300
313
326


Power Ten Second Data
900
800
700
600
500
400
kW
300
200
100
0
-100
-200
1
40
79
118
157
196
235
274
313
352
391
430
469
508
547
586
625
664
703
742
781
820
859
898
937
976

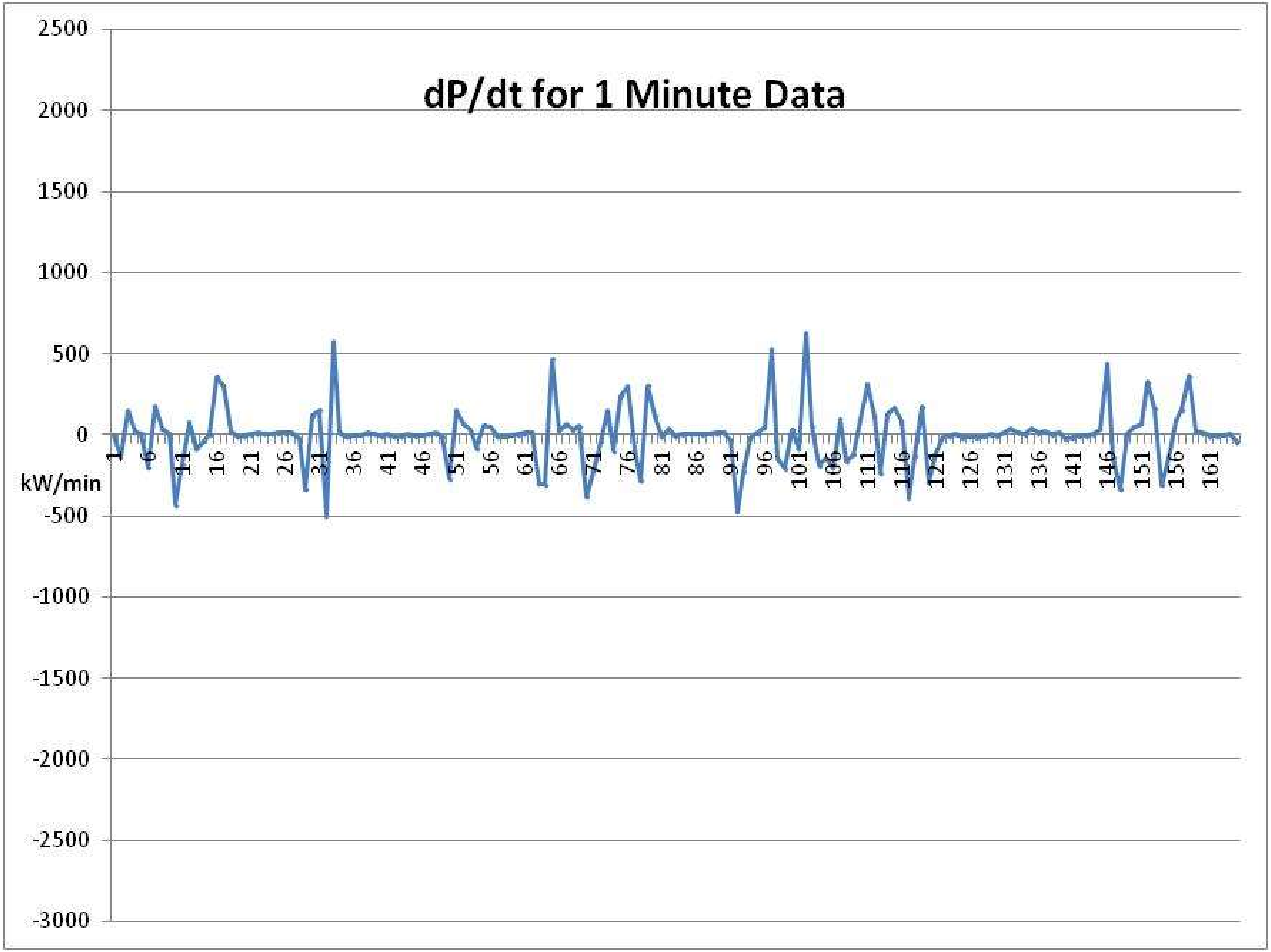

Power 1 Second Data
kW
900
800
700
600
500
400
300
200
100
0
-100
-200
1
401
801
1201
1601
2001
2401
2801
3201
3601
4001
4401
4801
5201
5601
6001
6401
6801
7201
7601
8001
8401
8801
9201
9601

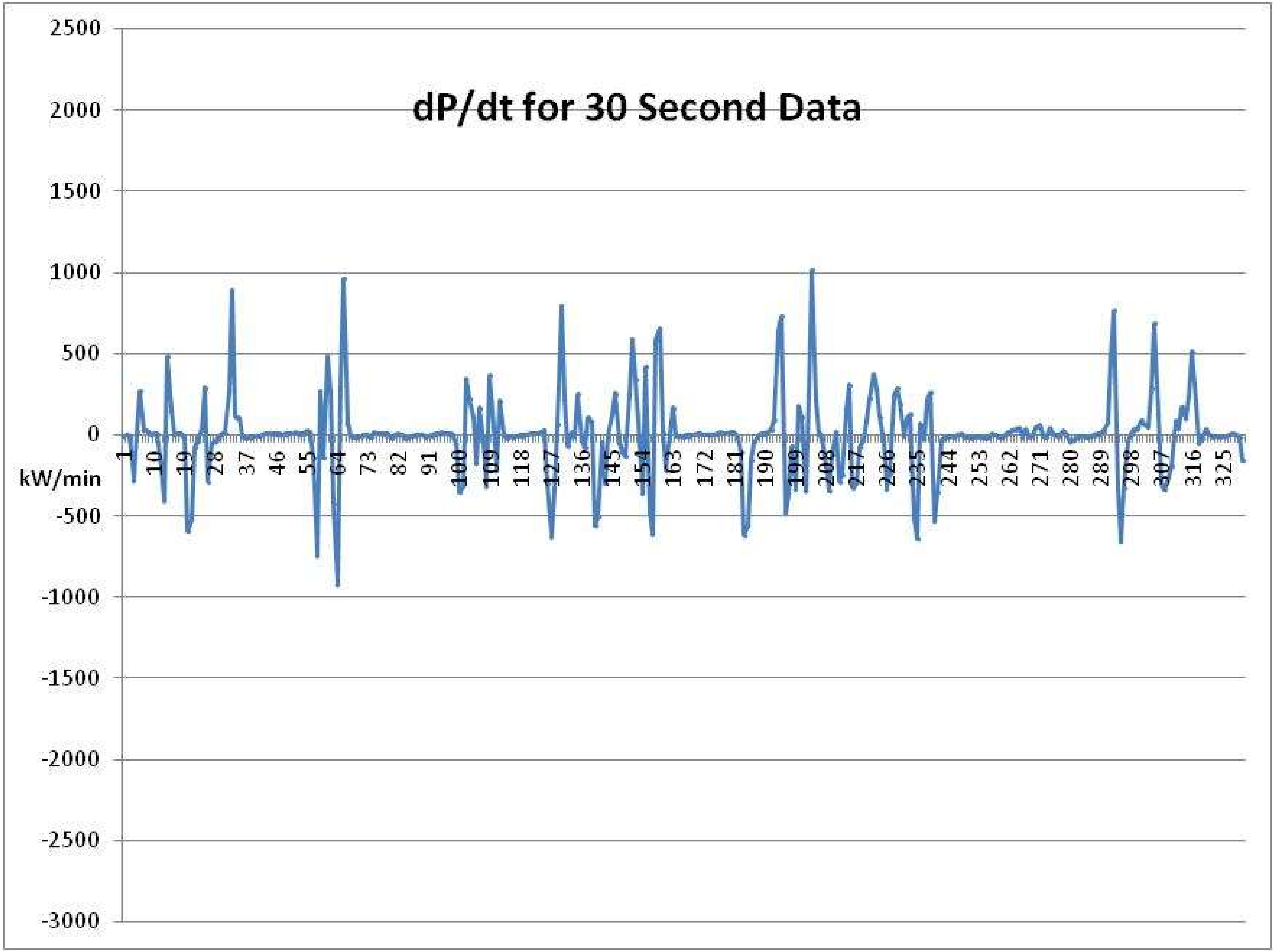

dP/dt for 1 Hour Data
2500
2000
1500
1000
500
0
kW/min
-500
-1000
-1500
-2000
-2500
-3000
1
2
3

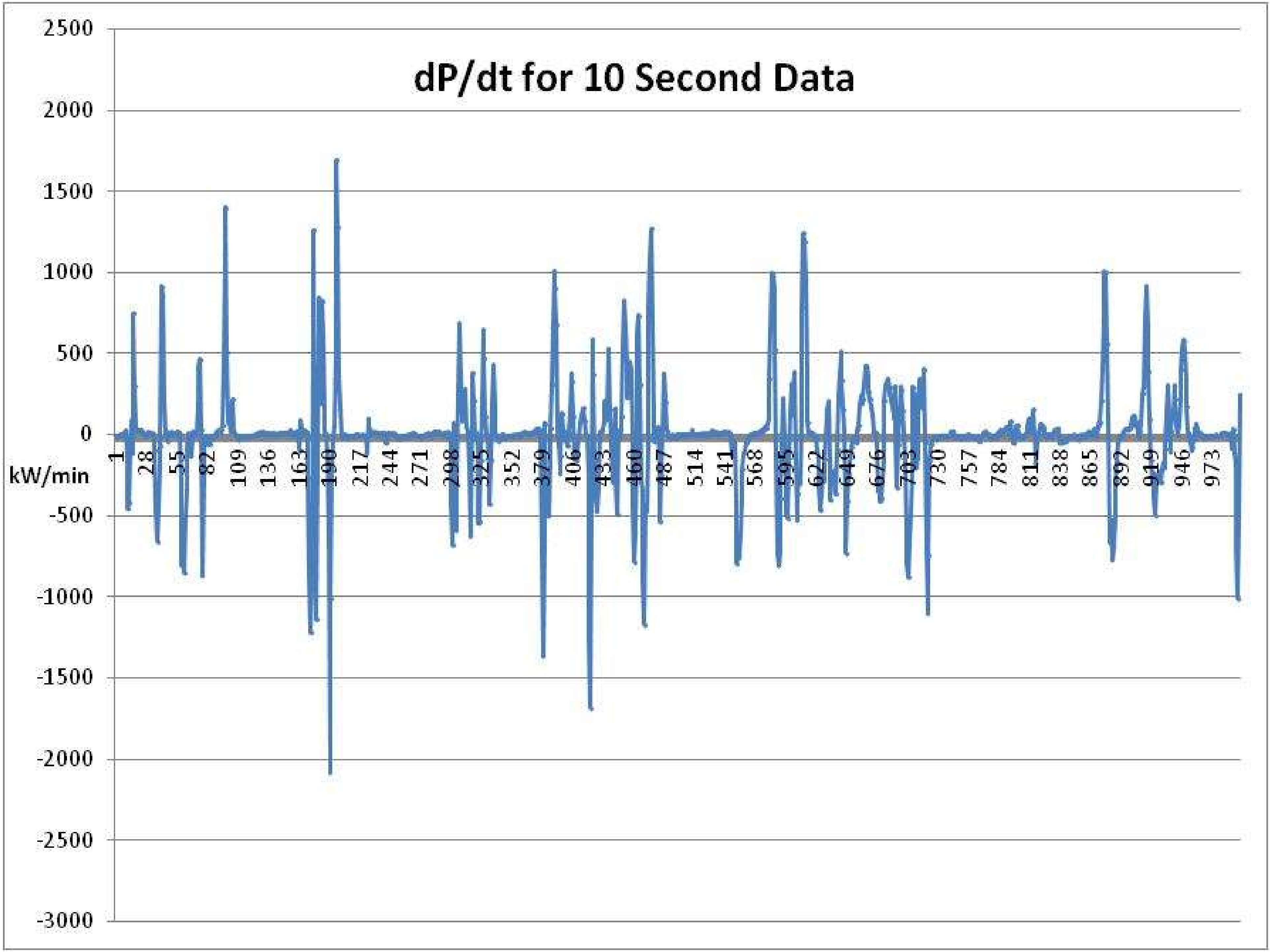

dP/dt for 15 Minute Data
2500
2000
1500
1000
500
0
kW/min
-500
-1000
-1500
-2000
-2500
-3000
1
2
3
4
5
6
7
8
9
10
11
12

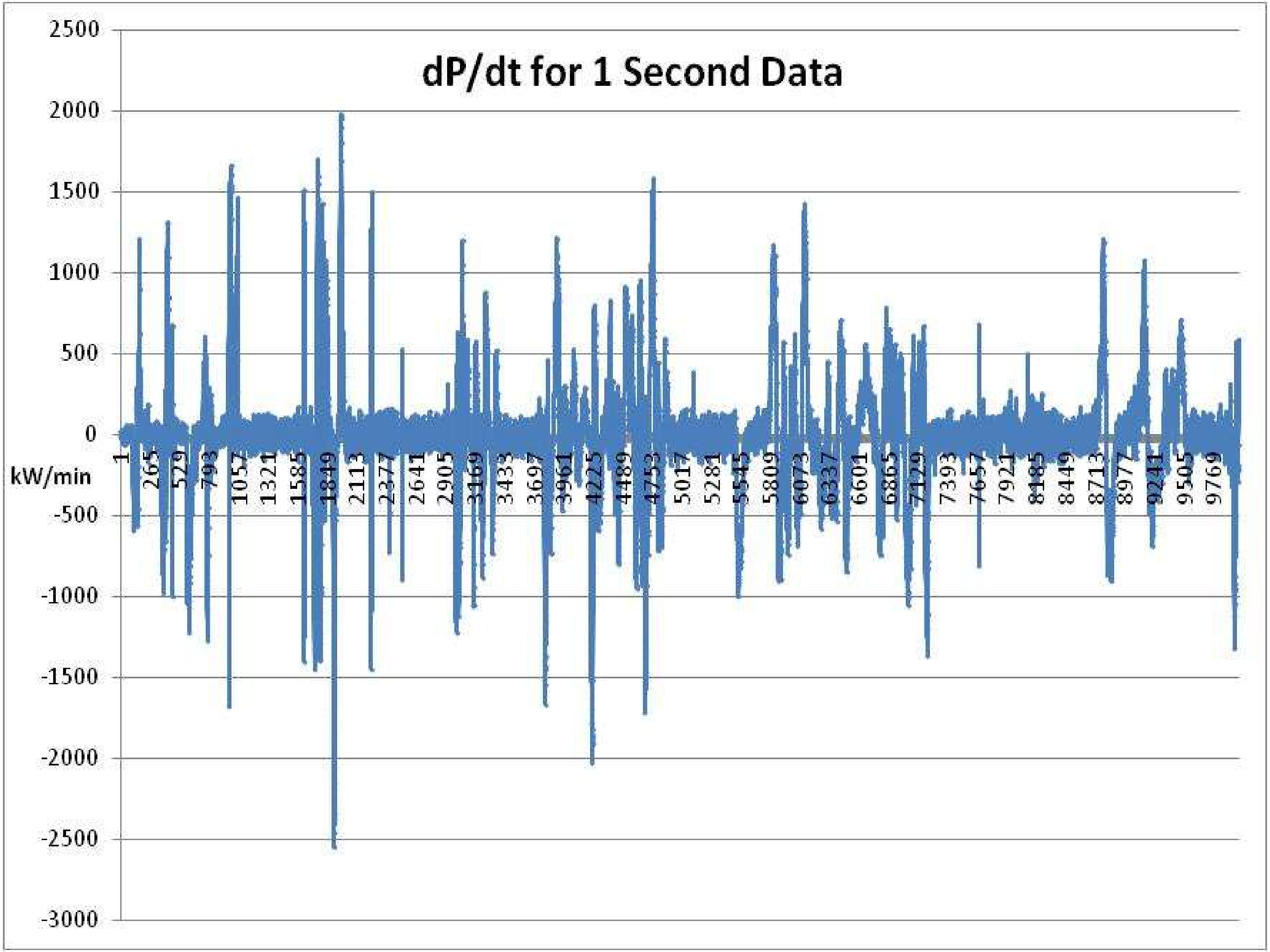


dP/dt for 5 Minute Data
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
kW/min
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34


dP/dt for 1 Minute Data
kW/min
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
86
91
96
101
106
111
116
121
126
131
136
141
146
151
156
161


dP/dt for 30 Second Data
kW/min
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
1
10
19
28
37
46
55
64
73
82
91
100
109
118
127
136
145
154
163
172
181
190
199
208
217
226
235
244
253
262
271
280
289
298
307
316
325


dP/dt for 10 Second Data
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
kW/min
1
28
55
82
109
136
163
190
217
244
271
298
325
352
379
406
433
460
487
514
541
568
595
622
649
676
703
730
757
784
811
838
865
892
919
946
973


dP/dt for 1 Second Data
kW/min
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
1
265
529
793
1057
1321
1585
1849
2113
2377
2641
2905
3169
3433
3697
3961
4225
4489
4753
5017
5281
5545
5809
6073
6337
6601
6865
7129
7393
7657
7921
8185
8449
8713
8977
9241
9505
9769

Addressing resource intermittence

Firming resources:

- load-following and reserve generation
- storage
- demand response

…whose effective and economical coordination depends on:

- good forecasts
- real-time data
- fast response
- good algorithms

important areas for continuing research – not just devices, but their coordination

Addressing resource intermittence

Firming resources:

- load-following and reserve generation
- storage
- demand response

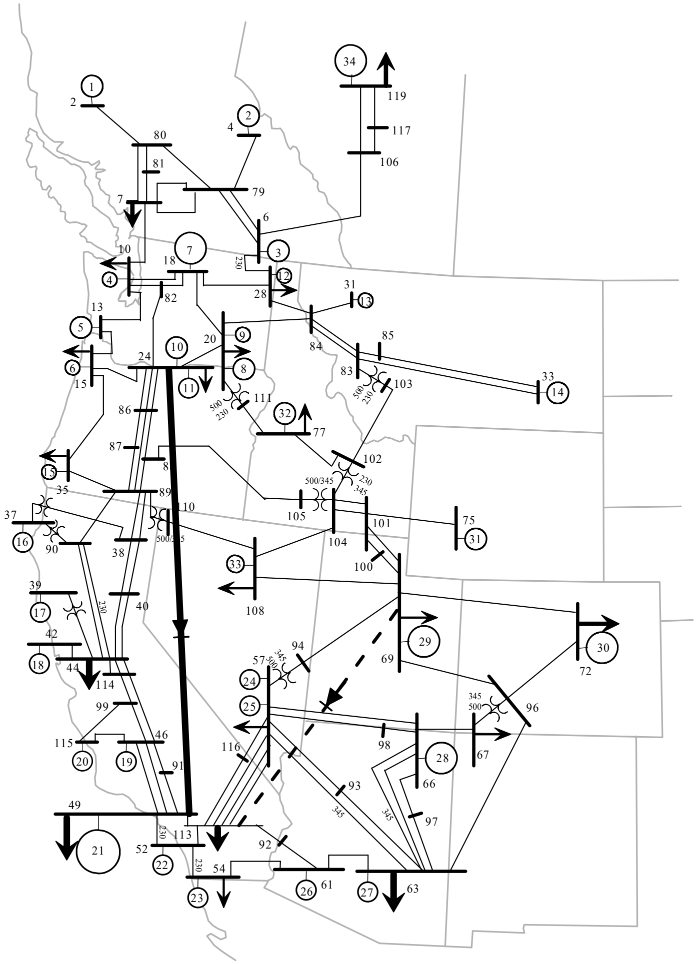
…on different time scales:

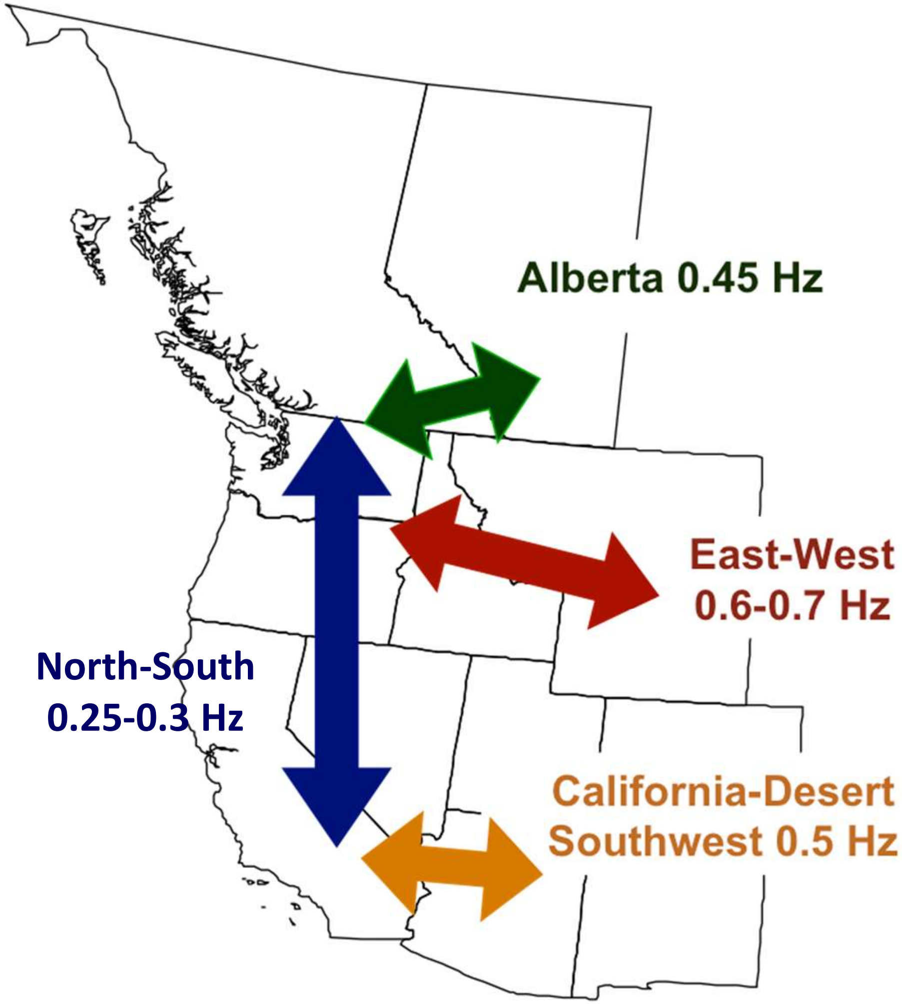
- seasonal
- day-ahead
- hour
- intra-hour
  - minutes
  - seconds
  - cycles

} frequency regulation, inertia

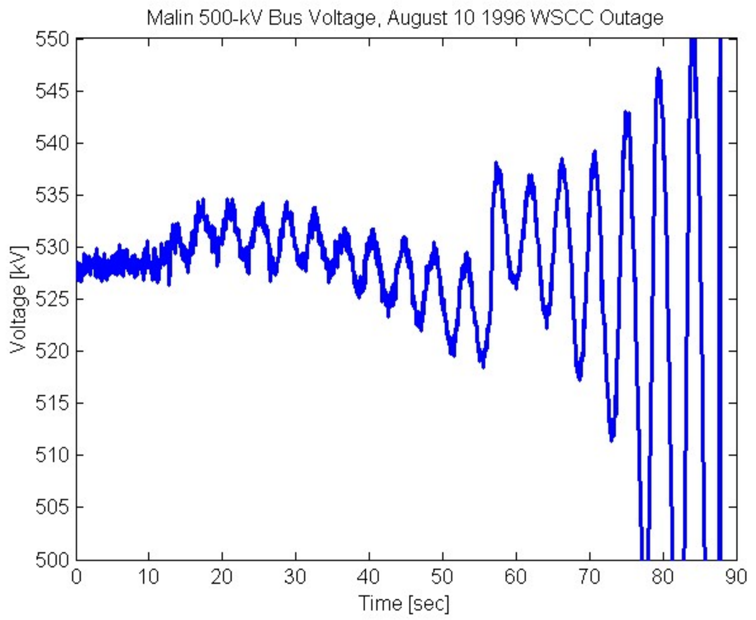
…suggesting new definitions of ancillary services?

Low-frequency oscillations in the Western U.S. grid



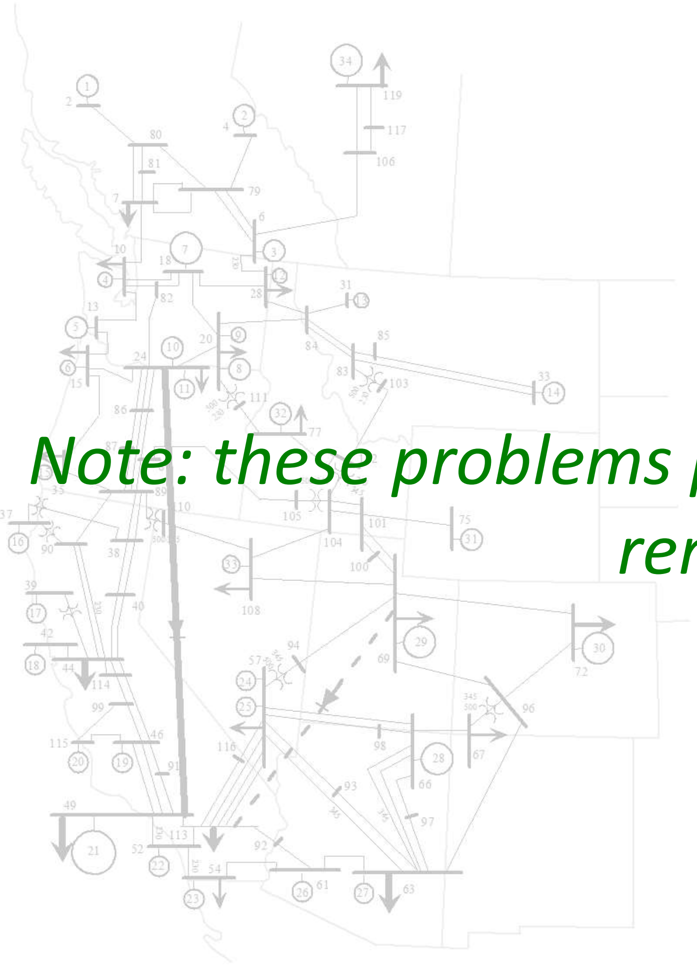


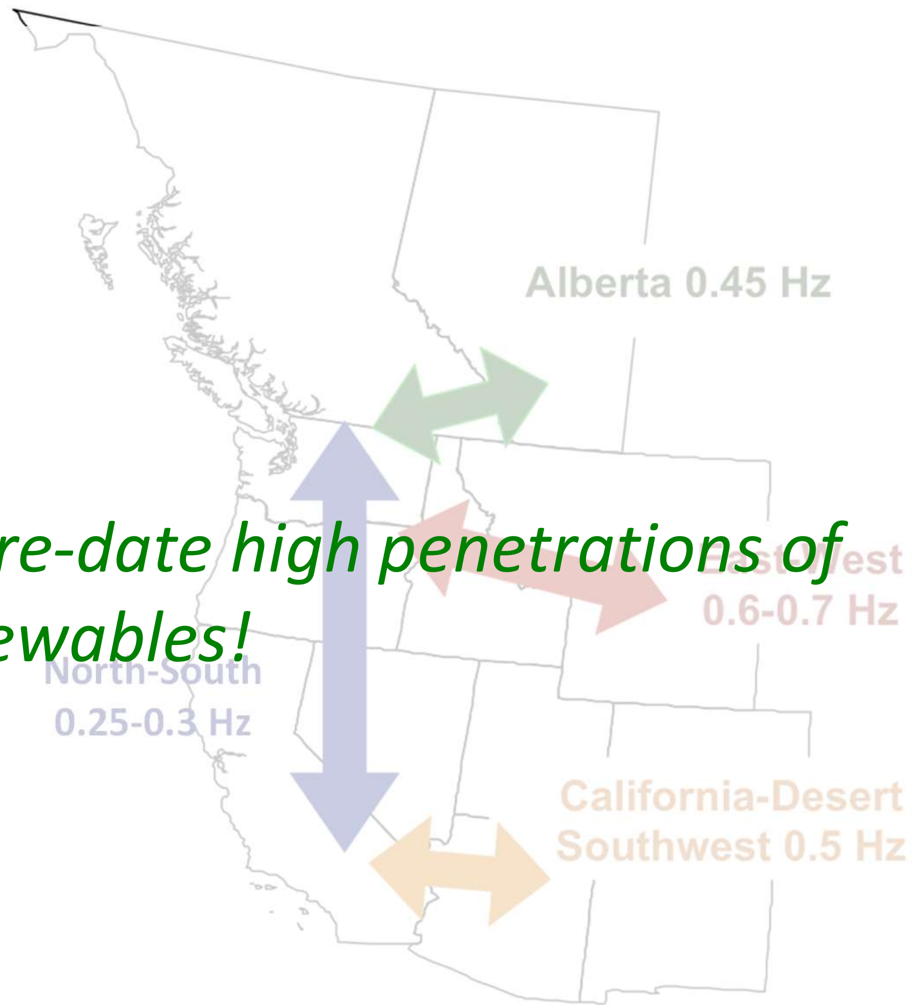
Example of North – South Oscillation…



…which ended in the August 10th, 1996 power outage in the Western U.S.

Low-frequency oscillations in the Western U.S. grid





Note: these problems pre-date high penetrations of renewables!

Coordination challenges in time

- Matching $P_{IN} = P_{OUT}$ on different scales
- Constrained by ramp rates (dP/dt) of resources
- Maintaining stability on the scale of seconds, cycles
- Long-distance a.c. transmission constrained by stability
- Impact of switch-controlled generators (inverters) on angle stability not yet well understood

Requires management at the sub-cycle level:

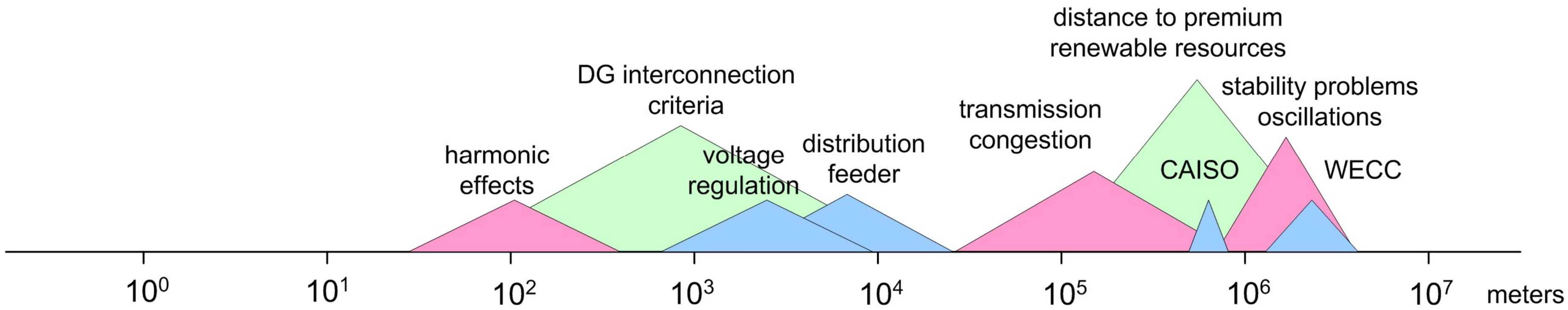
synchrophasors

ac-dc-ac conversion

power flow control devices

} chopping up waveform with solid-state technology

Distance scales in electric grid operation




www.trans-elect.com

Distribution vs. transmission systems

Important differences:

- architecture
- diversity
- time variation
- vulnerability
- opacity

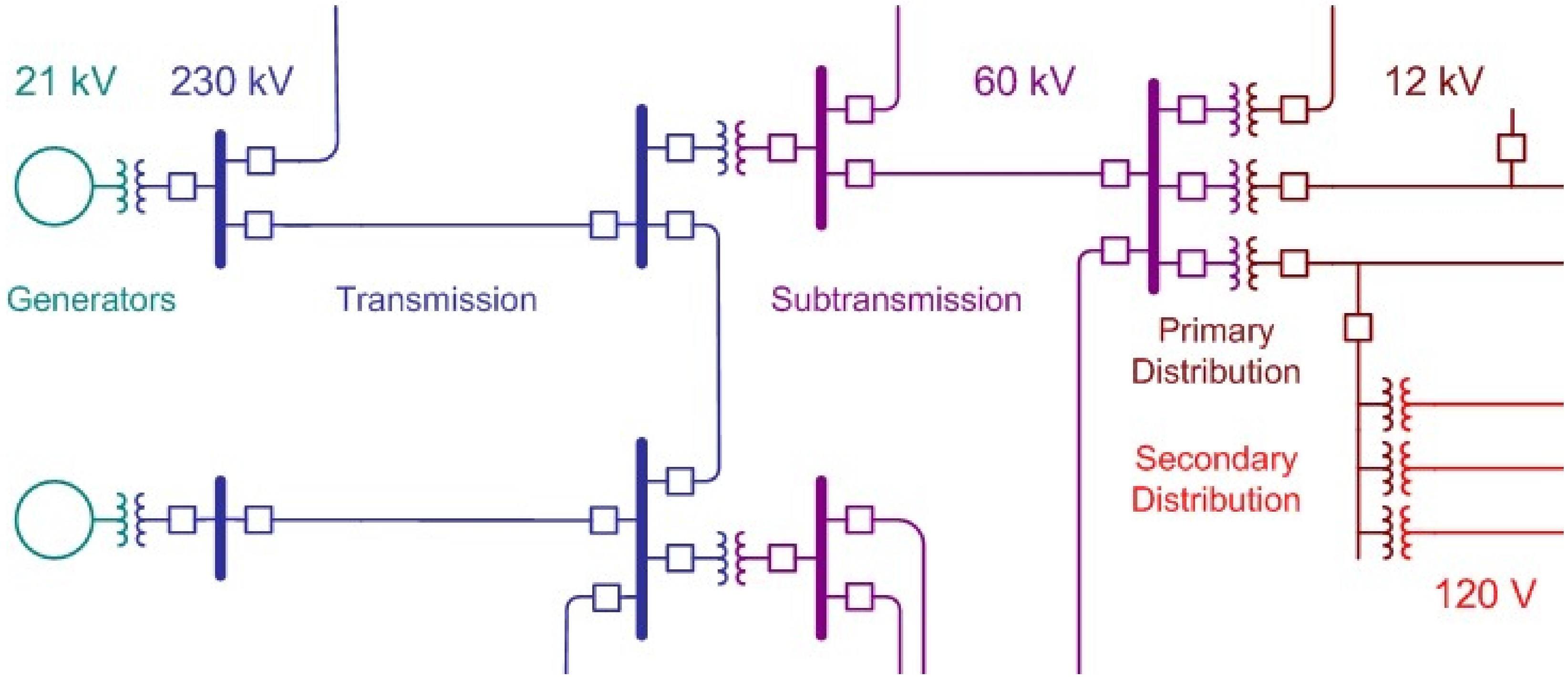
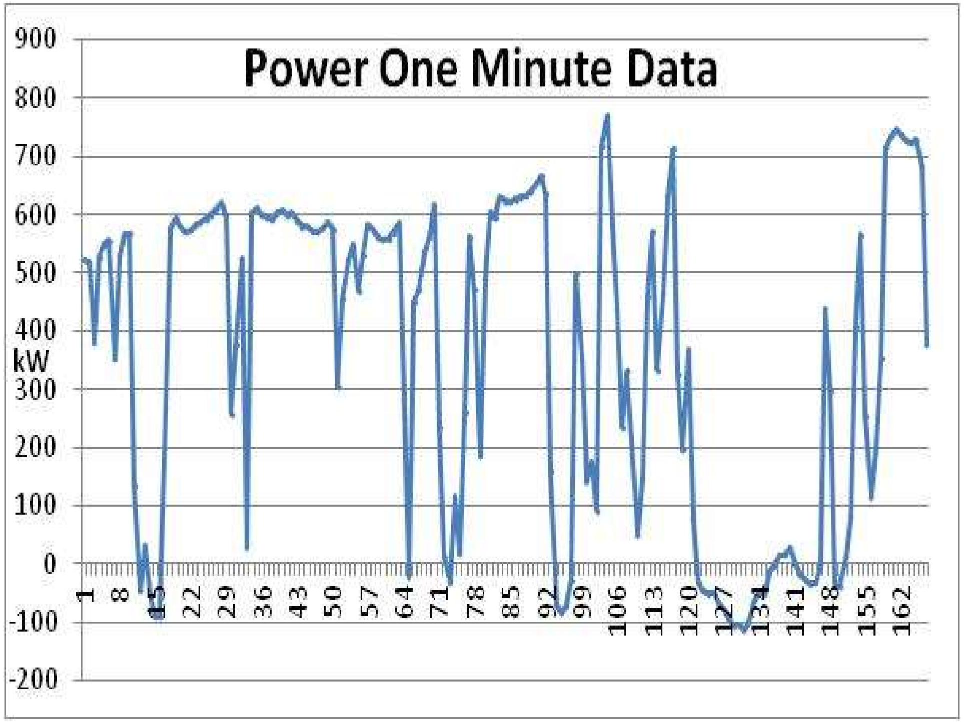


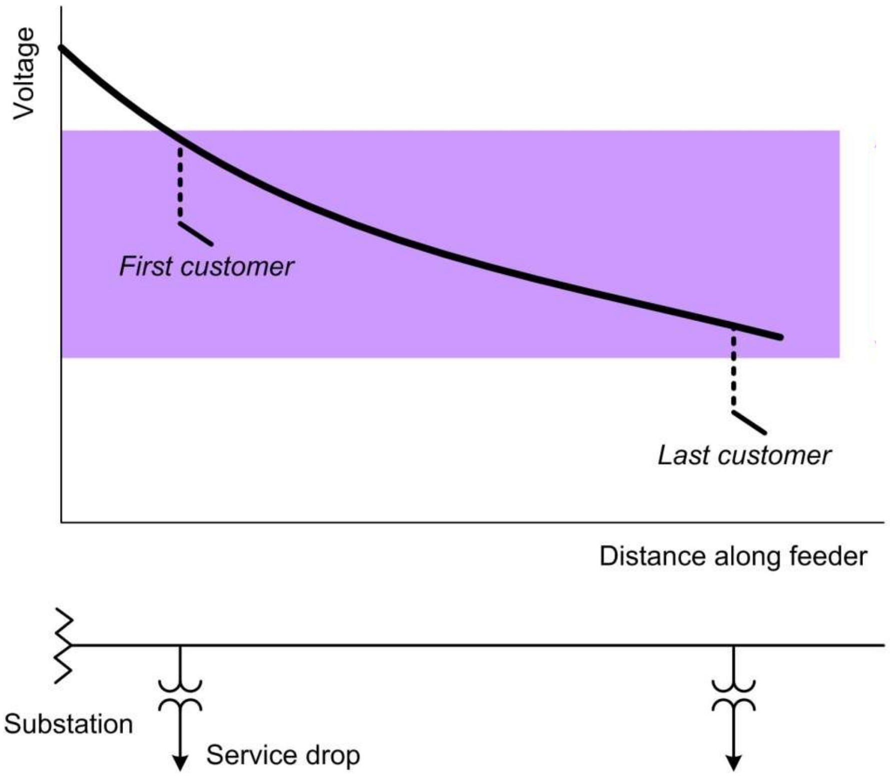
Illustration:
Michael Sowa

Distributed siting and local issues



- Generation and load modeling
- Voltage regulation
- Protection
- Islanding
- Unexpected phenomena

Distributed siting and local issues



- Generation and load modeling
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- Islanding
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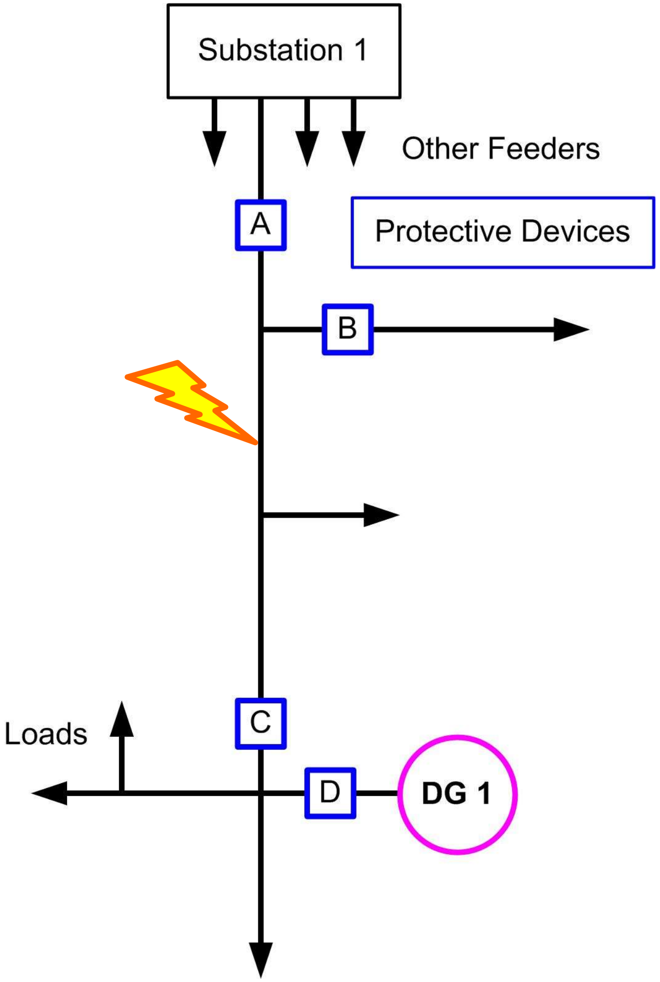
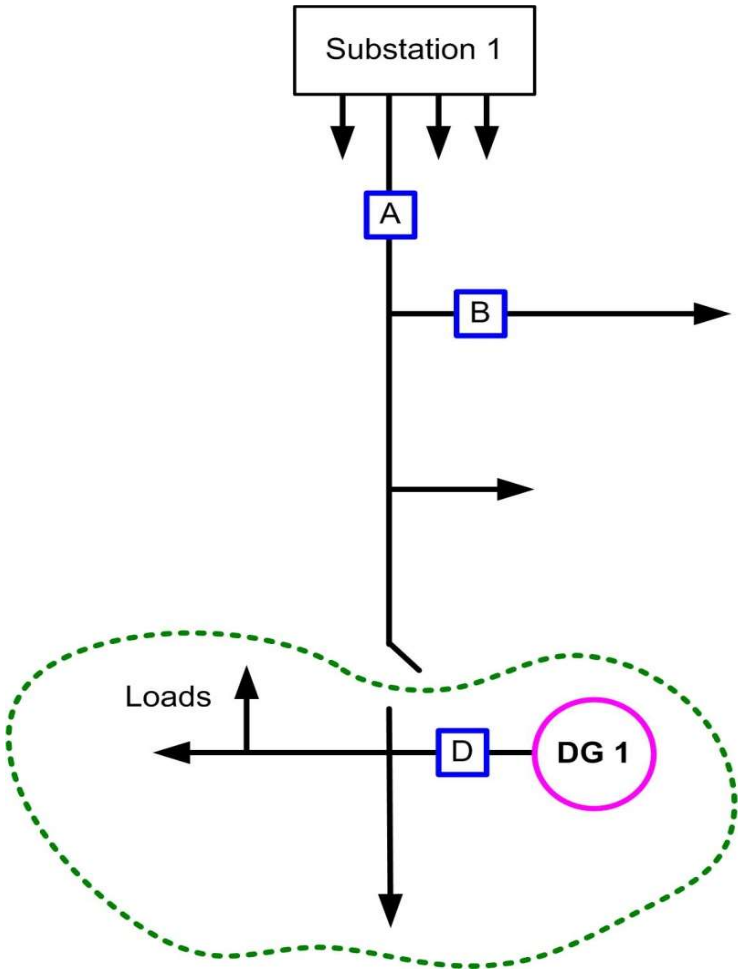
Distributed siting and local issues



- Generation and load modeling
- Voltage regulation
- **Protection**
- Islanding
- Unexpected phenomena

Distributed siting and local issues



- Generation and load modeling
- Voltage regulation
- Protection
- Islanding
- Unexpected phenomena

Distributed siting and local issues

- Generation and load modeling
- Voltage regulation
- Protection
- Islanding
- **Unexpected phenomena**

Distribution Monitoring Initiative

Distribution Monitoring for Renewables Integration
to be funded by PIER/California Energy Commission

collaborative effort with CA utilities
plan to install 3 line sensors each on ca. 20 circuits for each utility
sub-cycle sampling rates
include circuits with different penetration levels of DG installed

look for comparative impacts of DG
obtain baseline feeder behavior data
attempt typology of distribution feeders

use data to validate existing distribution circuit models

use data to develop and validate models of new components in distribution systems

Technologies under development
for refined observation and control

- four-quadrant (P,Q) inverters
  - volt-VAR control
- advanced inverters
  - harmonic cancellation
  - transient mitigation
- distributed storage
- micro-synchrophasors
- power routers
- solid-state transformer
- responsive loads
- communication networks

distributed resources & coordination tools

increasingly provide the capability to balance power and manage power quality & reliability locally

Future directions

Refined observation and control in time and space

- driven by the need to mitigate pre-existing vulnerabilities of the legacy system, much amplified by intermittent renewable resources
- providing the means to observe, communicate and control at higher resolution while maintaining large-scale awareness

Trend toward adding new capabilities on the grid's periphery

- resonant with philosophical and aesthetic preferences of many ratepayers who embrace "going local, going green"
- may enable more local diversity, flexible management options and more systemic value derived from renewable and distributed resources

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