Peak Load Management for Rapidly Developing Cities: Implications of Global Energy Service Provision Parity

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Contents

Motivation

Many of the world's **largest** and **fastest-growing** cities–from Karachi (pop. 14 million; 34.6% increase from 2000-2010) to Delhi (22m; 39.4%), Dhaka (15m, 45.2%), Jakarta (10m; 14.8%), Bangkok (8m, 29.1%), Lagos (11m; 48.2%) and Kinshasa (9m, 55.4%)–are located in South Asia and Sub-Saharan Africa with tropical to sub-tropical climates unlike those of most cities in the global North. As a result, it is important to consider how energy demand–particularly for thermal comfort–will evolve differently in these places. Figure 1 provides a map of urbanization rates for cities worldwide with a population greater than 750,000 (UN 2011). Urbanization rates are clearly highest in South Asia and Sub-Saharan Africa. Figure 2 shows the *distribution* of population growth rates for the same set of cities, grouped by latitude (global North, Tropics and Subtropics). The expected value (e.g. central tendancy) of urbanization rates in these regions are clearly distinct.

```
##     Continent Country.Code                          Country City.Code  Urban.Agglomeration Latitude
## 21       Asia           50                       Bangladesh     20119                Dhaka    23.72
## 228    Africa          180 Democratic Republic of the Congo     20853             Kinshasa    -4.30
## 279      Asia          356                            India     21228                Delhi    28.67
## 332      Asia          360                        Indonesia     21454              Jakarta    -6.13
## 452    Africa          566                          Nigeria     22007                Lagos     6.45
## 462      Asia          586                         Pakistan     22044              Karachi    24.87
## 550      Asia          764                         Thailand     22617 Krung Thep (Bangkok)    13.75
##     Longitude g50.60 g60.70 g70.80 g80.90 g90.00 g00.10 g10.20
## 21      90.41  51.28 170.46 137.72 102.74 55.345  45.16  34.39
## 228     15.30 119.34 141.55  91.91  71.46 53.817  55.43  46.43
## 279     77.22  66.72  54.65  57.43  74.97 61.757  39.43  33.46
## 332    106.75  84.49  46.17  52.84  36.62  2.622  14.78  20.85
## 452      3.40 134.43  85.40  81.97  85.21 52.825  48.18  46.69
## 462     67.05  75.61  68.28  61.86  41.59 40.353  34.58  31.33
## 550    100.52  58.15  44.59  51.87  24.67  8.018  29.13  24.99
```

```
##     Continent Country.Code                          Country City.Code  Urban.Agglomeration Latitude
## 21       Asia           50                       Bangladesh     20119                Dhaka    23.72
## 228    Africa          180 Democratic Republic of the Congo     20853             Kinshasa    -4.30
## 279      Asia          356                            India     21228                Delhi    28.67
## 332      Asia          360                        Indonesia     21454              Jakarta    -6.13
## 452    Africa          566                          Nigeria     22007                Lagos     6.45
## 462      Asia          586                         Pakistan     22044              Karachi    24.87
## 550      Asia          764                         Thailand     22617 Krung Thep (Bangkok)    13.75
##     Longitude g55.65 g65.75 g75.85 g85.95 g95.05 g05.15 g15.25
## 21      90.41 100.74 170.62 109.83  78.79 51.395  37.79  31.78
## 228     15.30 145.22 106.66  83.70  65.04 50.607  52.40  40.96
## 279     77.22  59.69  55.57  65.50  69.38 50.479  37.27  28.51
## 332    106.75  67.18  45.99  45.63  18.73  8.009  16.49  22.46
## 452      3.40 142.38  66.44  85.23  70.91 48.084  48.10  43.71
## 462     67.05  69.43  65.87  51.22  40.36 38.689  31.99  30.26
## 550    100.52  50.99  48.66  37.40  15.66 18.371  28.41  21.05
```

```
## [1] 0
```

```
## [1] 0
```

```
## [1] Continent           Country.Code        Country             City.Code
## [5] Urban.Agglomeration Latitude            Longitude           variable
## [9] value
## <0 rows> (or 0-length row.names)
```

```
## [1] TRUE
```

```
## [1] 0
```

```
## [1] TRUE
```

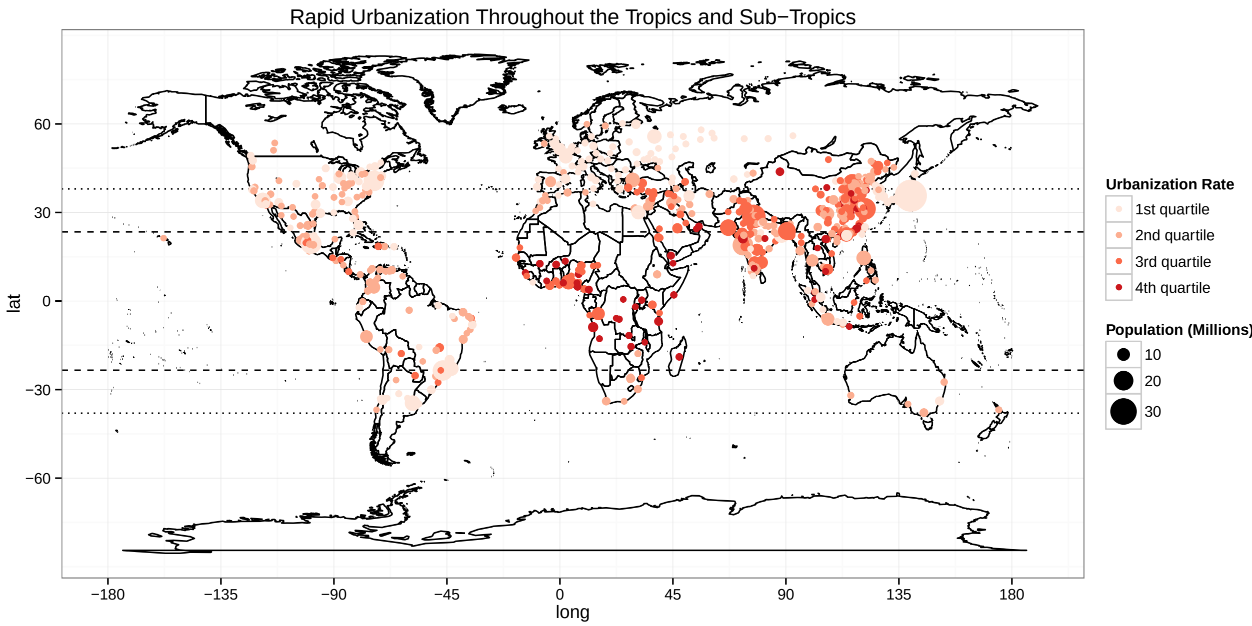
```
## 'data.frame':    9915 obs. of  12 variables:
##  $ Continent          : chr  "Asia" "Africa" "Africa" "Africa" ...
##  $ Country.Code       : num  4 12 12 24 24 31 31 32 32 32 ...
##  $ Country            : chr  "Afghanistan" "Algeria" "Algeria" "Angola" ...
##  $ City.Code          : num  20002 20035 20006 20050 20049 ...
##  $ Urban.Agglomeration: chr  "Kabul" "Wahran (Oran)" "El Djazaïr  (Algiers)" "Huambo" ...
##  $ Latitude           : num  34.54 35.75 36.76 -12.76 -8.84 ...
##  $ Longitude          : num  69.17 -0.63 3.05 15.75 13.23 ...
##  $ Period             : Factor w/ 15 levels "1950-1955","1955-1960",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ Growth             : num  7.18 1.26 3.75 8.84 4.61 ...
##  $ Growth.Bin         : Factor w/ 4 levels "[-43.9,1.64]",..: 4 1 3 4 4 1 1 3 3 3 ...
##  $ Growth.Quartile    : Factor w/ 4 levels "1st quartile",..: 4 1 3 4 4 1 1 3 3 3 ...
##  $ Year               : chr  "1955" "1955" "1955" "1955" ...
```

```
## [1] 0
```

```
## [1] TRUE
```

```
## [1] "NAs: 4"
## [1] "Complete Cases: FALSE"
```

```
## [1] "NAs: 0"
## [1] "Complete Cases: TRUE"
```



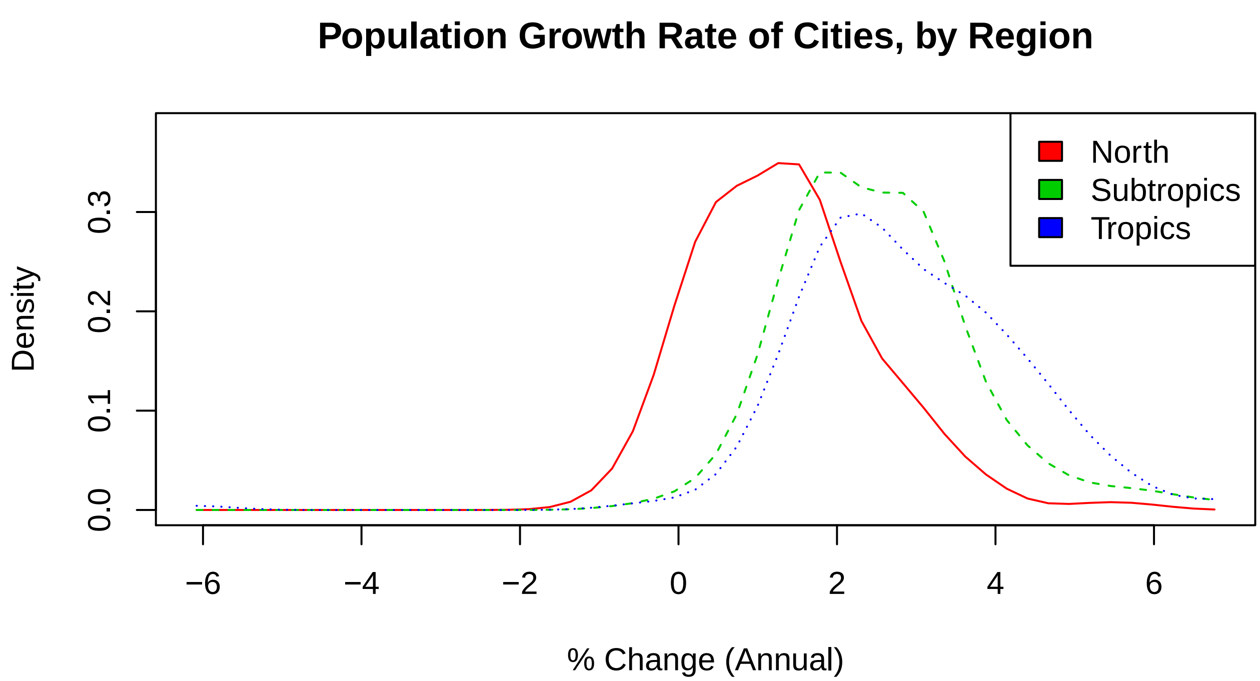

```
## [1] "World's Largest Cities in 2015 (Population > 10 million)"

##         Continent            Country             Urban.Agglomeration Population [MM]
## 1            Asia              Japan                           Tokyo            38.2
## 2            Asia              India                           Delhi            25.6
## 3            Asia              China                        Shanghai            23.0
## 4   North.America             Mexico   Ciudad de México (Mexico City)           21.7
## 5   North.America              U.S.A                New York-Newark            21.3
## 6            Asia              India                  Mumbai (Bombay)           21.2
## 7   South.America             Brazil                       São Paulo            21.0
## 8            Asia              China                         Beijing            18.1
## 9            Asia         Bangladesh                           Dhaka            17.4
## 10           Asia           Pakistan                         Karachi            15.5
## 11           Asia              India               Kolkata (Calcutta)           15.1
## 12  South.America          Argentina                    Buenos Aires            14.2
## 13  North.America              U.S.A Los Angeles-Long Beach-Santa Ana           14.1
## 14         Africa            Nigeria                           Lagos            13.1
## 15           Asia        Philippines                          Manila            12.9
## 16           Asia             Turkey                        Istanbul            12.5
## 17         Europe             Turkey                        Istanbul            12.5
## 18           Asia              China              Guangzhou, Guangdong          12.4
## 19  South.America             Brazil                  Rio de Janeiro            12.4
## 20           Asia              China                        Shenzhen            12.3
## 21           Asia Russian Federation                 Moskva (Moscow)            12.1
## 22         Europe Russian Federation                 Moskva (Moscow)            12.1
## 23         Africa              Egypt                Al-Qahirah (Cairo)          11.9
## 24           Asia              Japan                      Osaka-Kobe            11.8
## 25         Europe             France                           Paris            11.1
## 26           Asia              China                       Chongqing            11.1
## 27           Asia          Indonesia                         Jakarta            10.5
```

```
## 28        Africa              D.R.C                            Kinshasa            10.3
## 29          Asia              China                               Wuhan            10.3
## 30 North.America              U.S.A                             Chicago            10.2
## 31          Asia              India                           Bangalore            10.0
```

```
## [1] "World's Fastest Growing Cities (2010-2015) with a Population > 750,000"
```

```
##    Continent       Country  Urban.Agglomeration Growth.Rate [%]
## 1         Asia      Thailand         Samut Prakan            9.15
## 2         Asia      Viet Nam             Can Tho            8.78
## 3       Africa       Somalia Muqdisho (Mogadishu)            8.01
## 4       Africa Côte d'Ivoire         Yamoussoukro            7.52
## 5         Asia         U.A.E Abu Zaby (Abu Dhabi)            7.22
## 6       Africa  Burkina Faso          Ouagadougou            6.88
## 7         Asia     Indonesia                Batam            6.78
## 8         Asia         U.A.E       Dubayy (Dubai)            6.75
## 9         Asia         U.A.E              Sharjah            6.51
## 10        Asia         China               Xiamen            5.93
## 11        Asia         China      Suzhou, Jiangsu            5.92
## 12      Africa         Niger               Niamey            5.86
## 13        Asia         China         Wuhu, Anhui            5.81
## 14        Asia         China                Hefei            5.78
## 15        Asia         China             Yinchuan            5.77
## 16        Asia     Indonesia             Denpasar            5.74
## 17      Africa       Nigeria                Abuja            5.74
## 18        Asia         China             Jinjiang            5.63
## 19        Asia         China            Zhongshan            5.58
## 20        Asia         India             Tiruppur            5.34
```



To illustrate the potential for vast differences in energy demand for thermal comfort between cities in the global North and cities in the tropics/sub-tropics, consider Delhi, India. Delhi–with its massive population and very hot climate–is an outlier compared to cities in the global North but typical of South Asia: Peak summer temperatures routinely exceed 40 deg C. (104 F.), and intense heatwaves can approach 50 deg C. (122 F.). Given the huge temperature differential between outdoor (say 104 F.) and desired indoor air temperature (say 72 F), and the thermodynamic fact that energy for cooling scales linearly with that differential, cooling a room in Delhi will require twice as much energy as cooling a room in New York where the temperature differential is half that. As further evidence, in the past year, Delhi had over **six** times as many cooling-degree days as New York City, assuming an indoor air temperature of 72 deg F. Compounded by leaky building envelopes in developing world cities (designed for natural ventilation, not air conditiong), intense heat-island effects (typically less green space), and massive population growth, peak electricity demand in cities thourought the developing world could one day surpass that of their neighbors to the north–not only in aggregate terms because of their size, but also *per-capita* due to thermodynamics. That is, if we consider attaining energy parity between developed and developing world cities in terms of *service provision* rather than BTU or KWh, then we begin to understand the true magnitude of future energy demand, and associated resource consumption and environmental impact.

This has important implications not only for local/regional grid planning and reliability, but also the global transition to renewable energy given the limitations of meeting such large and 'peaky' demand with non-dispatchable resources such as wind and solar.

Rationale

Mid- to long-range energy demand forecasts are typically reported as annual totals and provide little insight to the distribution throughout the year. To address this shortcoming, we focus on the diurnal and seasonal distribution of energy demand and supply, which drive system cost but recieve relatively little attention in energy outlooks. This requires more and better data than is typically available to researchers.

Examples from India

This study presents an empirical analysis of diurnal-to-seasonal energy use patterns for 9 states in Northern India with a combined population of nearly 1/2 billion where we have data and prior experience. This analyses described here can serve as a methodological template for future analysis in other parts of the developing world, particularly in South Asia and Sub-Saharan Africa.

Methods and Materials

Each state is responsible for injection-load balance within its state periphery (e.g. power control area, or PCA) and coordination with the parent (regional) grid operator. Regional grid operators, in turn, are responsible for load balance within their region and coordination with the overarching national grid. This hierarchical structure offers a "natural experiment" for testing the effect of explanatory variables of interest such as climate, urbanization and income, while controlling for confounding factors such as power sector regulatory structure, pricing mechanisms, technology adoption, and technical expertise, which can be assumed to be similar for all States operating in the same regional grid.

The Northern Region Load Dispatch Center (NRLDC) is charged with injection/load balance for the entire Northern Region (NR) of India, including coordination of 9 constituent State Load Dispatch Centers (SLDCs) located in the region, and the National Load Dispatch Center (NLDC), which handles inter-regional energy exchanges to maintain overall grid frequency and stability. The NR is the largest of 5 regional power grids, supplying 273,240 GWh in 2012/13 and meeting a peak demand of 41,790 MW.

The NRLDC maintains power system data for each of the 9 constituent states and the region as a whole. The data is publically available on their website, but only for downlaod as PDF. Batch downloading and converting PDF to readable format (e.g. csv) is messy, cumbersome and prone to errors. To side-step this limitation, and to better utilize available data, a JavaScript was developed to "scrape" HTML from inside the NRLDC web browser. Post-processing and subsequent data analysis was performed in RStudio using markdown language.

Data analyzed for this study was derived from a daily report published by the NRLDC entitled "Power Supply Position in the Northern Region". The pertinent data can be summarized as follows: * Regional Availability and Demand: Evening-Peak (MW), Off-Peak (MW), Day-Energy (GWh)
State Control Area Details: Generation (GWh), Drawal (GWh), Use (GWh)
State Demand Met: Evening-Peak (MW), Off-Peak (MW), Day-Energy (GWh) * Stationwise Details: Installed/Declared Capacity (MW), Peak/Off-Peak/Average Sentout (MW), Schedule/Unscheduled Interchange (GWh)

Regional Energy Availability and Demand

First, we explore the daily demand profile of the Northern Region (NR). For clarity, we apply weekly smoothing to the daily data. **Figure 1. Time series of energy supply and shortages in the NR grid (2011-14)**

Figure 2. Comparing seasonality of energy supply, energy shortages and energy requirement for Northern India

An important first question is when do shortages arise? From Figure 1 we may glean that they are not strictly seasonal nor confined to peak summer months when demand is highest. To confirm, we boxplot energy shortages by month and examine their relative distributions. We see that median energy shortage is highest in October and July, with July having the highest variability of any month. Median energy shortage is lowest in the winter months.
Figure 3. Monthly boxplots of daily energy shortages in Northern India

If the magnitude of energy shortfalls (e.g. energy not supplied; ENS) is not strictly seasonal, perhaps peak shortages as a fraction of peak demand, is. In other words, do certain months experience higher rates of load-shedding at peak times?
Figure 4. Seasonality of peak shedding as fraction of peak demand
Similar to Figure 2, we see the greatest variance in July, but here the median is fairly stable, with peak shedding 5-10% of peak demand in all months.

As another check, we examine energy shortages as a function of total energy supplied. This helps answer the question: Do shortages increase as demand increases? We would expect this to be true if capacity adequacy was the limiting factor.
Figure 5. Scatterplot of Energy Shortage vs. Energy Supplied

Figure 6. Daily energy shortages [in GWh] for the NR grid, with weekly and monthly smoothing

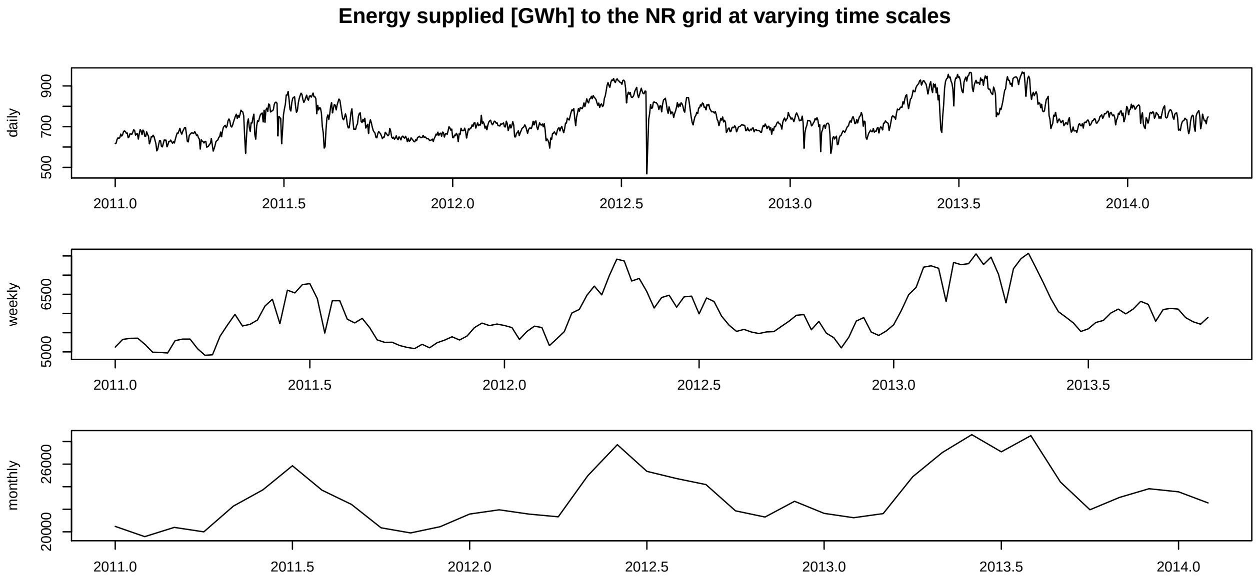


Figure 7. Daily energy supply [in GWh] for the NR grid, with weekly and monthly smoothing

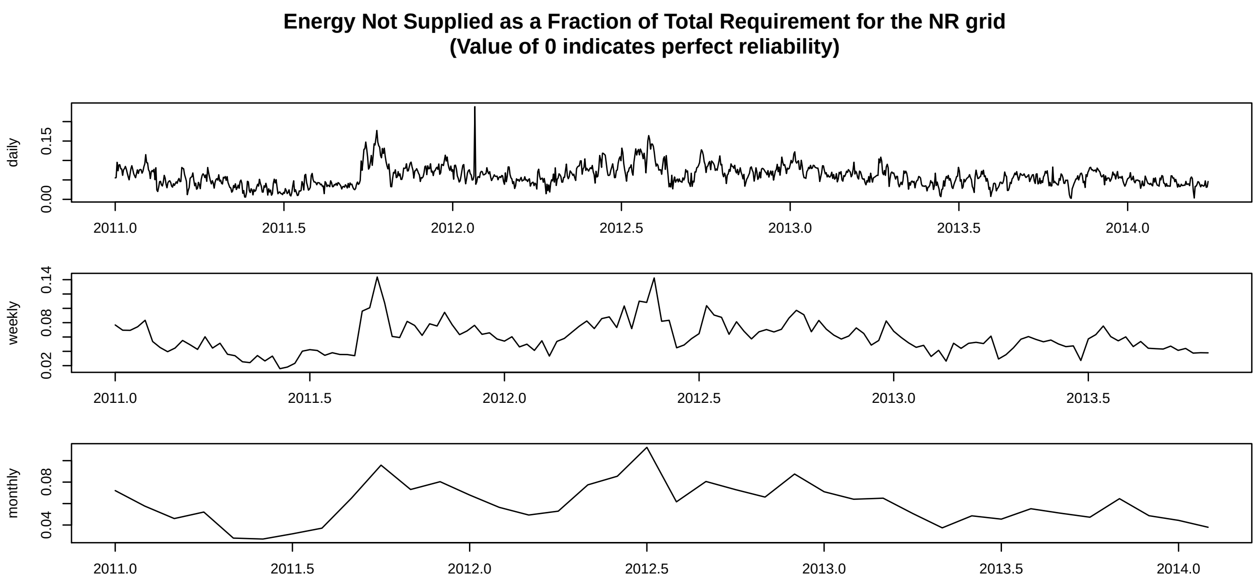


Figure 8. Fraction *Energy Not Supplied* to the NR grid, with weekly and monthly smoothing

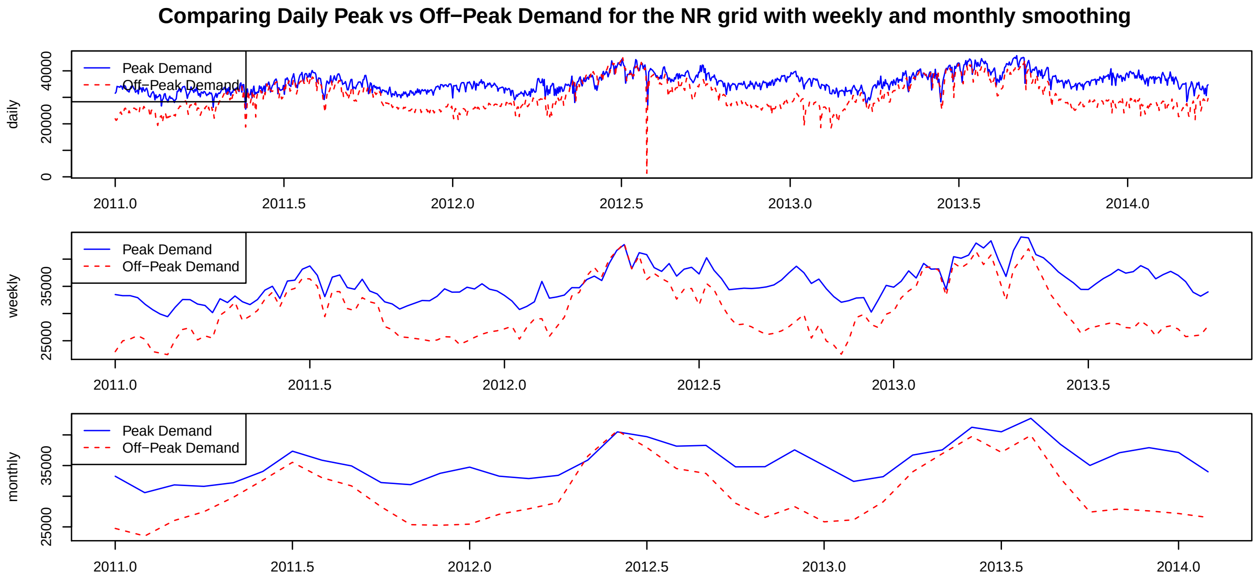


Figure 9. Comparing Daily Peak vs Off-Peak Demand for the NR grid with weekly and monthly smoothing