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Modeling Interregional Transmission Congestion in the National Energy Modeling System

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Environmental Energy
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Prepared for the Planning Analysis and Evaluation Section of the
Planning Budget and Analysis Program
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Acronyms and Abbreviations

AEO	Annual Energy Outlook
DOE	U.S. Department of Energy
ECAR	East Central Area Reliability Coordination Council EMM region
ECP	Electricity Capacity Planning submodule of NEMS
EERE	Energy Efficiency and Renewable Energy of DOE
EFD	Electricity Fuel Dispatch submodule of EMM
EIA	Energy Information Administration of DOE
EMM	Electricity Market Module of NEMS
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
FL	Florida EMM region
GPRA	Government Performance and Results Act of 1993
GW	gigawatt (10^9 watts)
GWh	gigawatt-hour
LBMP	locational based marginal price
LBNL	Lawrence Berkeley National Laboratory
LBNL-NEMS	LBNL version of NEMS
LP	linear programming
MAAC	Mid-Atlantic Area Council EMM region
MW	megawatt (10^6 watts)
MWh	megawatt-hour
NEMS	National Energy Modeling System
NERC	North American Electricity Reliability Council
NWP	Northwest Pacific EMM region
NY	New York EMM region
NYISO	New York Independent System Operator
PAE	Planning, Analysis, and Evaluation section of PBA
PBA	Planning Budget and Analysis Program of EERE
RA	Rocky Mountain, Arizona, New Mexico, Southern Nevada EMM region
RON	rest of NEMS
SERC	Southeastern Electric Reliability Council EMM region
TWh	terawatt-hour
WECC	Western Electricity Coordinating Council

Definitions

Coal regions – breakdown of the U.S. within NEMS by coal producing areas. These define where new coal plants are built, regardless of the electricity regions that build them.

Dedicated and Detached Grid – this refers to the set of new transmission capacity that NEMS builds for generating plants, which are dedicated to serving load in a different region from which they are built. These out of region builds are almost always coal plants.

Doubled Case – this case represents the Reference Case with a doubling of the transmission grid capacity limit by 2025.

Electricity regions – breakdown of the U.S. within NEMS by grouping electricity supply and demand. NEMS does not track electricity transmission within regions, only between electricity regions.

Groups – twelve characteristic hours in a year, represented as any combination of the four seasons (winter, spring, summer or fall) and three times of the day (night, midday, morning/evening)

Groupment – a set of hours that LBNL-NEMS characterizes as equivalent. A total of 36 hours represent the year when calculating capacity planning and transmission in LBNL-NEMS. Each groupment (group combined with segment) is defined by three aspects: season (winter, spring, summer or fall), time of day (night, midday, morning/evening), and load magnitude (high, medium, normal). Each aspect is further explained in Appendix B.

LBNL-NEMS – refers to the Berkeley Lab modified version of NEMS to avoid confusion with the official release of NEMS maintained by EIA.

NEMS – this term is used when generically referring to this EIA forecasting model. For example, when explaining how coal regions are defined in NEMS, this definition applies to both NEMS and LBNL-NEMS.

No CaFl Coal Case – this case represents the Reference Case without coal builds for California and Florida.

Non-simultaneous limit – maximum transimission capability between a pair of nodes assuming all other network power injections remain constant. This type of limit is used in the transportation model.

Power Flow Case – this case represents the Reference Case with reduced transmission limits. This case is further explained in Section 2.

Reference Case – this case is similar to AEO 2004 Reference Case except that the transmission limits are defined for all 36 unique periods each year, where AEO only defines four sets of unique transmission limits each year to cover the 36 time periods for which the dispatch solves.

Segment – one of three divisions of hourly demand within any group of hours where the first segment is the highest 1% of hourly demand, the second segment is the next highest 33%, and the third segment is the remaining 66% of hourly demand.

Simultaneous limits – the sets of transmission limits between nodes that can be simultaneously reached in the transmission model.

Transmission model – also referred to as a *power flow model* - is a detailed model that represents the interdependencies of energy flow along different paths in the system.

Transportation model – also referred to simply as a *transport model* – is a simple model for representing flows of a quantity through a network by assuming the flows along differing paths are independent. This is the model used in NEMS and is fundamentally different than the physical characteristics of the power grid which is better represented by a transmission model.

Executive Summary

Historically, major blackouts seem to have brought calls for upgrading the U.S. transmission system. More recently, the chorus is stronger and more constant. The lack of investment in the grid is widely deplored as a leading cause of poor reliability and increasing congestion. While extremely complicated to fully comprehend, analysis of national grid capability is becoming a vital policymaking need. A common indicator of an economically inadequate grid is congestion, which by definition implies the cheapest availably supply cannot be used; therefore a less-congested system can lead to lower electricity prices and less frequent power outages.

To help reduce transmission grid congestion, the Department of Energy's (DOE) Energy Efficiency and Renewable Energy (EERE) Program supports many potentially helpful technologies. Some of these include microturbines, combined heat and power, fuel cells, photovoltaics, and energy efficient appliances. These technologies offer the ability to reduce system load, site generation close to load, and thereby expand effective grid capacity. These benefits may be significant, particularly with respect to lowered congestion costs, generation costs, and system investments.

To begin evaluating the benefits of reduced congestion, Berkeley Lab has tried to use the transmission and congestion modeling in the Energy Information Administration's (EIA) National Energy Modeling System (NEMS) including exploration of a promising new approach to better represent interregional transfers of electric power. This complex task is divided into three parts: understanding how the existing North American transmission system operates, understanding how NEMS represents interregional transfers of electric power, including how the generation construction logic inherent in NEMS limits its ability to consider significant changes in interregional transfers, and, finally, given all this, assessing how how to measure benefits of technologies that affect transmission congestion.

Berkeley Lab expects to eventually measure benefits by correlating scenarios with less congestion with lower electricity prices and less transmission investment and failure. At the present time, neither NEMS, in its official configuration, nor NEMS, as enhanced by Berkeley Lab, can fully capture these impacts. These limitations, there sources, and possible ways to address them, are the subject of this report. . As far as reliability benefits, less congestion can be indicative of less stress on the electric grid. NEMS was not designed to capture this impact and it is not the subject of this report.

Interregional Transmission in NEMS

The U.S. is divided into 13 electricity regions in NEMS, and transmission structured to model between regions, but not within them. There is limited international electricity transmission with Canada and Mexico.

According to the Annual Energy Outlook (AEO) 2004 Reference Case, total interregional transmission is decreasing over time. Gross domestic electricity trade is reduced from 222 TWh in 2003 to 179 TWh in 2025 as shown in Figure ES-1. It is of critical importance for the subject of this investigation to recognize that this result is a modeling artifact. That is, the generation logic inherent in NEMS automatically builds new generating capacity close to load. In order words, the NEMS model, by its very formulation, decreases dependence on interregional transmission to meet

future electricity demands. Thus, it is no surprise that interregional congestion is also forecasted to decrease using Berkeley Lab's version of NEMS called LBNL-NEMS. In 2015, 31% of total interregional line-hours[1] are fully loaded or congested, while in 2025 congestion is reduced to 23% as shown in Figure ES-2. Additionally, in 2015, 37% of total interregional line-hours are unused, though by 2025, fully 45% of line-hours are idle. This amount of unused transmission capacity seems unrealistic. However, the power flow limits in NEMS overstate the available transmission capacity, which could account for some of the excess capacity.

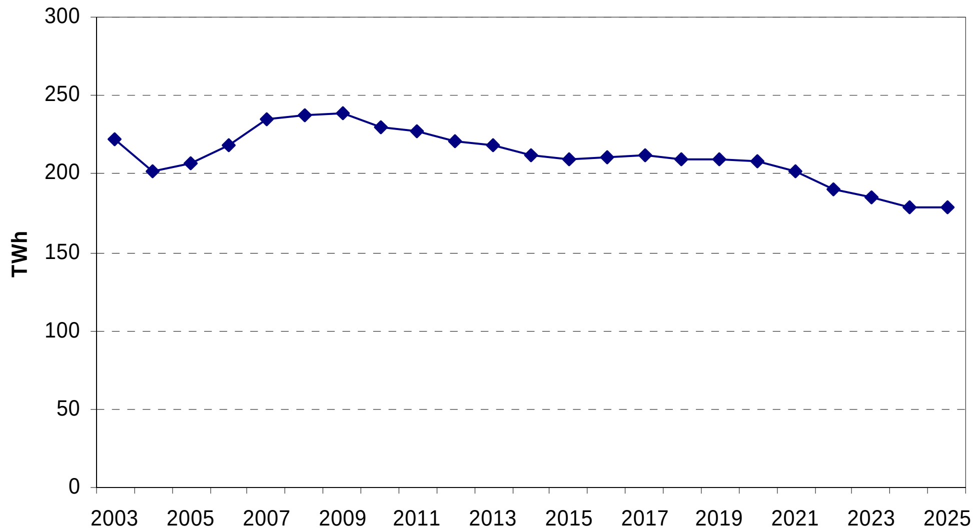


Figure ES- 1 Economic Transmission in the Reference Case

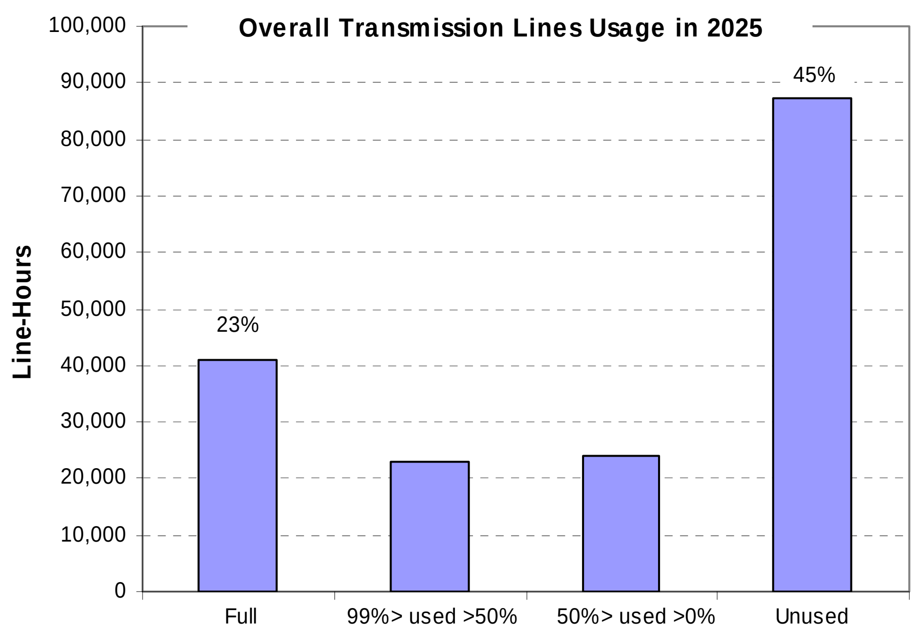


Figure ES- 2 Line Congestion Forecast, 2025

[1] Annual domestic interregional line-hours total 175,200. This number is the product of the number of domestic interregional connections (20) and the available hours for transmission in a year (8,760).

Power Flow

The LBNL-NEMS power flow is calculated using a *transportation* model, not a *transmission* model. A transportation model assumes that the flow of energy along different paths can be specified independently, similar to the representation of a transportation network. Each individual automobile driver chooses their route independently, and if a driver takes a particular route, it does not affect the routes chosen by other drivers. In contrast, a transmission model of an electric grid enforces the physical laws that make energy flow along different paths dependent. As an analogy to power flow, the reader may consider water flowing through a network of pipes without valves. When pressure is applied at one location, the flows along all connected pipes are affected simultaneously. The flow along each pipe depends on the physical characteristics of the pipe and the applied water pressure. To see this affect on the transportation network, one driver's choice to take a particular route would have to simultaneously force other drivers to take certain other routes in the network. The important implication of this difference between models is that the transportation model will always tend to overestimate the maximum transfer capabilities of the electric grid.

To compare the interregional transmission forecast from LBNL-NEMS using its default transportation model (Reference Case) with a forecast mimicking the use of a more accurate transmission model (Power Flow Case), Berkeley Lab was able to mimic the effect of a true power flow. Given the differences between the models, Berkeley Lab anticipated a decrease in transmission usage with a transmission model. Berkeley Lab used PowerWorld™ Simulator[2] (PowerWorld), a proprietary power flow software product that solves the transmission among regions. Using the PowerWorld solution from the LBNL-NEMS dispatch, Berkeley Lab redefined the LBNL-NEMS transfer limits. This illustrated that this method was successful by iterating LBNL-NEMS with PowerWorld. While the transmission forecast is different, the Power Flow Case does not lead to much change in the fuel mix, installed generating capacity, or energy consumption, compared with the Reference Case. Perhaps most importantly, introducing the transmission model did not increase congestion significantly.

As noted above, this result is hardly surprising because both NEMS, and by extension, LBNL-NEMS include a generation construction logic that acts to reduce future interregional transfers of electricity. As a result, regardless of the representation of the transmission system, the driving forces for interregional transfers (which are differences in the price of electricity generation across regions) are absent.

Reducing Congestion

Berkeley Lab created a doubled transmission case (Doubled Case) to test the opposite effect, increasing transmission and reducing congestion. This case was created by gradually expanding the transmission capacities 10% annually over 10 years starting in 2016 until it is doubled in 2025. Domestic trade did increase minimally for the Doubled Case, at most by 10% (2020-2025), and congestion was reduced. However, other indirect effects of reducing congestion were hard to

[2] This is commonly referred to as "PowerWorld" in industry, which is the convention that will be used in this report.

identify as congestion is only peripherally related to the size of the transmission grid. These results, confirm, as previously noted, there are more fundamental obstacles to using LBNL-NEMS for congestion analysis, namely, the generation expansion logic of NEMS and LBNL-NEMS.

Dedicated and Detached Grid

One anomaly that Berkeley Lab noted was that there is very little congestion in the West. This is in part due to the fact that the AEO 2004 Reference Case forecasts 12 GW of new coal capacity to be built for California by 2025. Realistically, it seems unlikely that much coal will be built for California in the near future. Therefore, a no new coal for California and Florida case (No CaFl Coal, for short), was implemented. In the No CaFl Coal Case, economic interregional transmission is up 20% and congestion increases, particularly in the western U.S. These results were the first indication that the generating capacity expansion logic in NEMS plays a more significant role in determining future congestion than upgrading the transmission grid (Doubled Case).

To better understand these results, Berkeley Lab conferred with EIA, which maintains the NEMS model. They explained that NEMS can build new natural gas capacity with dedicated interregional transmission that is, for all intents and purposes, not connected to the transmission grid (Energy Information Administration 2005b). Perhaps the best way to visualize this assumption is to think of this natural gas fired capacity as capacity that is directly connected to a load center via a DC transmission line such that flows on this single line of connection do not interact or affect power flows on the rest of the transmission system. As a result, this dedicated transmission is not considered interregional transmission, so this capacity expansion logic leads to underreporting of interregional electricity trade, for the purposes of this analysis. In addition, coal plants are built according to the NEMS coal regions rather than the electricity regions. Coal regions and electricity regions are quite different and have no direct mapping to one another. However, when solving for electricity transmission, the coal plants are designated as operating in the region where their owner is located, which corresponds to the NEMS electricity regions. In other words, electricity transmission from a coal plant to its owner region becomes a strictly intra-regional transfer.

New coal plants never use the existing transmission grid and NEMS does not determine whether a new coal plant requires interregional transmission or not. Although at least 17 GW of new coal plants are built out of region, ironically, new plants lead to less interregional transmission. A whole set of dedicated plants and interregional transmission lines are built which make up a network detached from the existing transmission grid.

Only certain types of generating plants can be built off the existing grid and the associated transmission capacity is referred to in this study as the *dedicated and detached grid*. A dedicated and detached grid helps explain why congestion on the visible grid is reduced over time and why potential benefits from reducing congestion, consequently will be underestimated.

Conclusions

Congestion analysis using NEMS or NEMS-derivatives, such as LBNL-NEMS, is subject to significant caveats because the generation logic inherent in NEMS limits the extent to which interregional transmission can be utilized and intraregional transmission is not represented at all. The EMM is designed primarily to represent national energy markets therefore regional effects may be simplified in ways that make congestion analysis harder. Two ways in particular come to mind. First, NEMS underutilizes the capability of the traditional electric grid as it builds the dedicated and detached grid. Second, it also undervalues the costs of congestion by allowing more transmission than it should, due to its use of a transportation model rather than a transmission model.

In order to evaluate benefits of reduced congestion using LBNL-NEMS, Berkeley Lab identified three possible solutions: 1) implement true simultaneous power flow, 2) always build new plants within EMM regions even to serve remote load, and 3) the dedicated and detached grid should be part of the known grid.

Based on these findings, Berkeley Lab recommends the following next steps:

- Change the build logic that always places new capacity where it is needed and allow the transmission grid to be expanded dynamically.
- The dedicated and detached grid should be combined with the traditional grid.
- Remove the bias towards gas fired combine cycle and coal generation, which are the only types of generation currently allowed out of region.
- A power flow layer should be embedded in LBNL-NEMS to appropriately model and limit transmission.

1. Using NEMS to Evaluate Transmission Grid Congestion

1.1 Background

The objective of this effort is to introduce a more realistic representation of power flows between regions using the Lawrence Berkeley National Laboratory's (LBNL) version of the National Energy Modeling System (NEMS), or LBNL-NEMS. The benefits of this work are potentially significant given the poor representation of congestion severely limits potential markets for many technologies being developed in the Energy Efficiency and Renewable Energy (EERE) Program (Moore et al. 2005; National Research Council 2005). National scale energy modeling is necessary in support of the annual Government Performance and Results Act (GPRA) analysis, and for other EERE decision-making. Electricity availability is artificially high while prices are artificially low[3] in many regions where many EERE technologies have the greatest potential.

The NEMS model represents markets as homogeneous constructs covering the entire or large portions of the country with similar consumers facing uniform prices. The manageable level of disaggregation in large models is limited by analytic and computing capability as well as by available data. Judicious analytic choices must be made so that consistency of approach is achieved, and results can be reaggregated to levels comparable to large national models. Therefore, at the same time that markets must be judiciously reduced to comprehensible pieces that better represent highly heterogeneous market segments, the resulting segments must be ones that fit conveniently into existing models and available data sets.

Much of the Planning Analysis and Evaluation (PAE) Section of the Office of Planning, Budget, and Analysis (PBA) of EERE analysis is conducted using NEMS, so focusing on this model is fully appropriate. Despite its limitations, NEMS has some key advantages: first, it is maintained by a significant number of Energy Information Administration (EIA) analysts who carry the burden of keeping data sets up-to-date and ensuring the model is functioning correctly; second, it enjoys great currency in federal policymaking circles in large part because it is so heavily reviewed; and third, it provides the basis for the Annual Energy Outlook (AEO), which is the most widely used forecast of the U.S. energy sector and a natural starting point for PAE analysis.

Not surprisingly, much of the thrust of the PAE analytic agenda addresses the fundamental problem of market disaggregation, with the goal of better identifying and characterizing the environment in which EERE technologies will compete. The work fits squarely in the class of market analyses that attempt to deconstruct large aggregated markets, albeit in a very limited but important way.

Currently in NEMS, transfers between regions are limited only by simple economics and a *transportation model* of transmission, i.e. one that only limits flows to a constant predetermined limit. This structure has long been known to be an inadequate representation of actual grid transfer capability, which is limited by congestion remote from actual interties of interest, and which varies moment-by-moment as flows change. However, retooling LBNL-NEMS to use a more realistic power flow representation of the grid, a *transmission model*, is a major undertaking for a number of reasons. One key problem is that the expansion and operation of the power system is considered

[3] Appendix A compares the NEMS forecast of electricity prices and loads for the state of New York with data from the New York Independent System Operator.

independently, region by region, so even if the capability of the grid to deliver energy across regional boundaries is adequately represented, the economic incentives and technical feasibility of transfers will still be inadequate. This work takes a limited approach, with a strict focus on the interregional transfer capability, particularly because any new LBNL-NEMS functionality will likely need to be reintroduced into the current AEO.

Over time, EIA is likely to adopt many of the LBNL-NEMS enhancements developed for the PAE analyses, however this process is lengthy and uncertain. A wise approach to developing LBNL-NEMS therefore, is to build new capabilities in an add-on way; that is, to develop additional models and/or LBNL-NEMS code that can be reactivated each year in the GPRA cycle without incurring an undue programming burden. In this example, the power flow capabilities are modeled using a commercial power flow model that can be run in parallel with LBNL-NEMS using the existing power system that LBNL-NEMS builds year-by-year.

1.2 Limitations of NEMS Transportation Model

Figure 1-1, below, shows the *electricity regions* and transfer limits that are used by NEMS. These regions are essentially nodes in a network where all supply and demand are collapsed to a single point. In other words, there is no geographic variability within regions, only between them. NEMS enforces these limits in a transportation model. NEMS represents the contiguous U.S. by a superset of the North American Electricity Reliability Council (NERC) regions with separation of California and New York and further subdivision of the remaining Western Electricity Coordinating Council (WECC) region. The Canadian provinces appear as nodes distinct from the NERC regions they are actually attached to, and there is one node in Mexico. The transfer capabilities between regions used in the AEO 2004 Reference Case version of NEMS are depicted in the figure (in GW). These limits are allowed to vary by season, although in current data only two are used, summer and winter. In some cases the transfer capabilities are symmetric, and in others they differ depending on the direction of flow. The values for these transfer limits are treated as constant inputs in NEMS and do not change throughout the simulation; in other words, the grid is not sensitive to economic opportunities for expansion.

The values for the transfer limits originate from NERC transfer limit studies. NERC prepares summer and winter path limits between NERC regions for *non-simultaneous* flows. Given a nominal base case, non-simultaneous flow is the amount of power that can be transferred from one defined region to another, *assuming all other power injections remain constant*. In practice, many economic trades between regions happen *simultaneously*, and the non-simultaneous limits cannot all be applied at once, i.e. they are not independent. In practice, a detailed power flow will show that when one path reaches its power flow limit, it will effectively limit the ability to transfer power along other paths. If the first path is congested, then an attempt to increase power along a second path may not be allowed depending on whether it would require increasing the flow along the already-constrained first path.

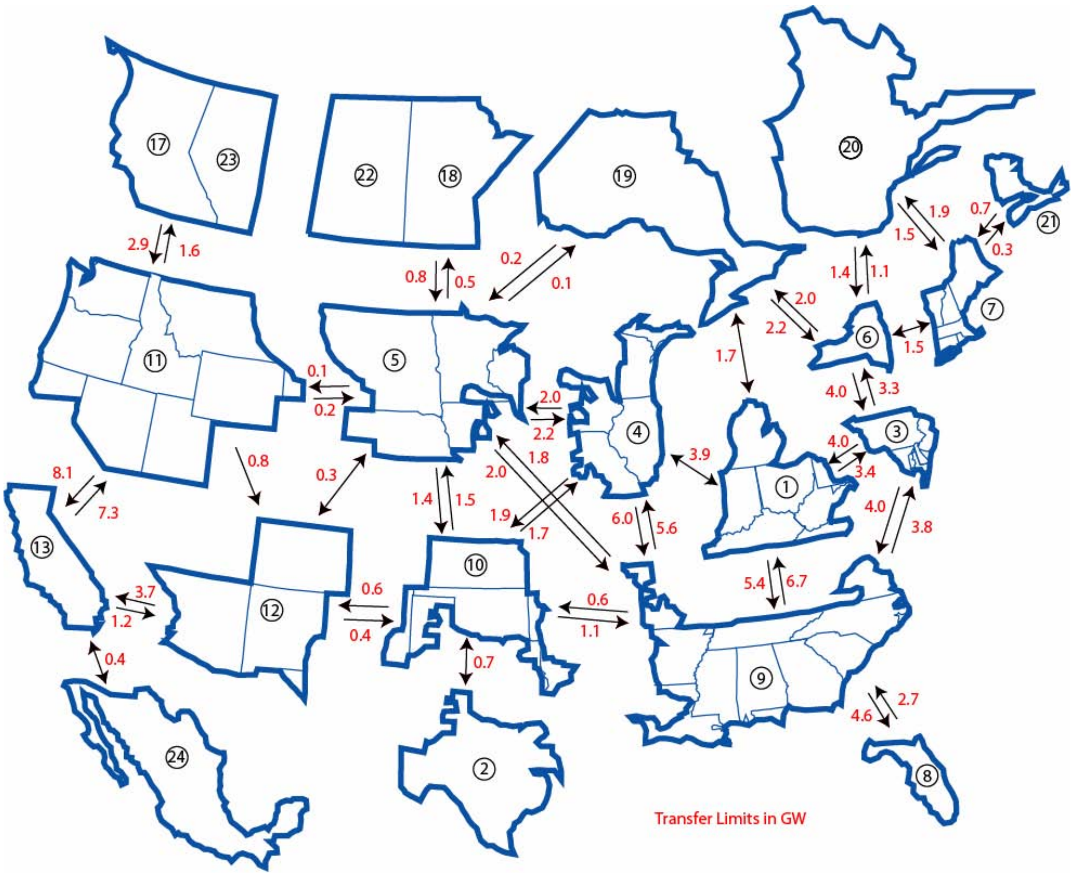


Figure 1-1 Transfer Limits in NEMS for Summer and Fall 2004 (GW)

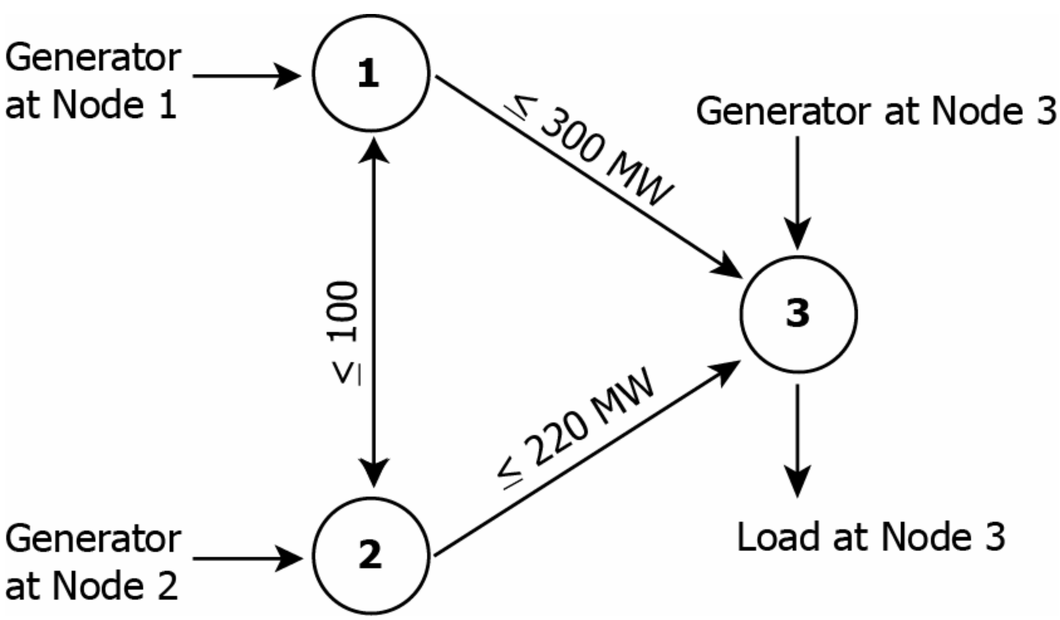


Figure 1-2 Power Flow Limits in a Three-Node Example

A well known three-node example, shown in Figure 1-2, illustrates flaws in the transportation model. The actual intertie capabilities between the three nodes are shown. In the three-node example, there are generators at nodes 1, 2, and 3, but load only at node 3. Assume that generator 3 is out of service. A transportation model assumes that power flow may be directed along the paths in any manner that suits a particular dispatch goal. It is possible to specify a 300 MW flow between nodes 1 and 3, 220 MW between nodes 2 and 3, with no power flow between nodes 1 and 2. Alternatively, one might make more use of the generator at node 1 and specify that it supply 400 MW if it is more economic. Then, 300 MW flows from nodes 1 to 3 and 100 MW flows from node 1 to node 2 and subsequently to the demand through the path from node 2 to node 3. Any remaining demand is supplied by the generator at node 2 up to 120 MW (at which point all three lines reach their capacity limits simultaneously).

In reality, the flow along each path is not independent. In this example, a flow from node 1 to node 3 cannot be simultaneously specified independent of the flow from node 1 to node 2. As an example, suppose we assign equal electrical impedances to each path. Then, the power that is supplied to the network by the generator at node 1 is distributed unequally among the path from node 1 to node 3 and the longer path from node 1 to node 2 to node 3. Two-thirds of the power flows along the short path and one-third flows along the long path. Consequently, neither of the dispatches mentioned in the previous paragraph are physically possible. This dependent power flow characteristic of the electricity grid limits the capability of the system, almost always reducing the transfer capabilities compared to a transportation model.

A nomogram is a diagram that shows the actual transfer capability of a transmission system, which is shown in Figure 1-3 for the same three-node example. Here we show the nomograms for both the *transportation* model (dotted line) and the *transmission* model (solid line and shaded area). Each frontier shows the maximum transfer capability to node 3, with the x-axis showing transfer from node 1 to node 3 and the y-axis from node 2 to node 3. The following summarizes this diagram for each model:

- The nomogram for the transportation model is bounded by the three dashed lines. These lines represent the maximum amount of power that can be injected into the system from node 1 (400 MW is the sum of capacity limits on lines leaving node 1), the maximum amount of power that can be injected in to the system from node 2 (320 MW is the sum of capacity limits on lines leaving node 2), and the maximum amount of power that can be delivered to node 3 (520 MW is the sum of line capacities connected to node 3).
- The nomogram for the transmission model is more complex and lies wholly within the nomogram of the transportation model. Note that the maximum transfer capability of 520 MW is only achieved at one point. At all other combinations of generation from generators 1 and 2, this limit is not reached. The reason is that congestion on the line 1 to 2 always prevents sufficient flow on the other two lines. Also note that congestion in a grid limits its capabilities on lines remote from the congested line, which is why this study of congestion is so important.

The difference between the nomograms exemplifies the primary deficiency of a transportation model. It neglects the reality that congestion on remote lines (from line 1 to 2 in this case) limits flows on lines of interest. If the line limits imposed within the NEMS transmission model reasonably reflect the actual physical capacity of lines, the net capability of the system will almost certainly overestimate actual capability, as shown in Figure 1-3. From the perspective of many EERE technology-based programs that can serve to alleviate interregional congestion, the full congestion relief benefits are not being accurately accounted for. Better representing the true limits of the grid should raise prices in congested areas and vice-versa, thereby identifying potential niche markets where early penetration of emerging technologies are likely to benefit.

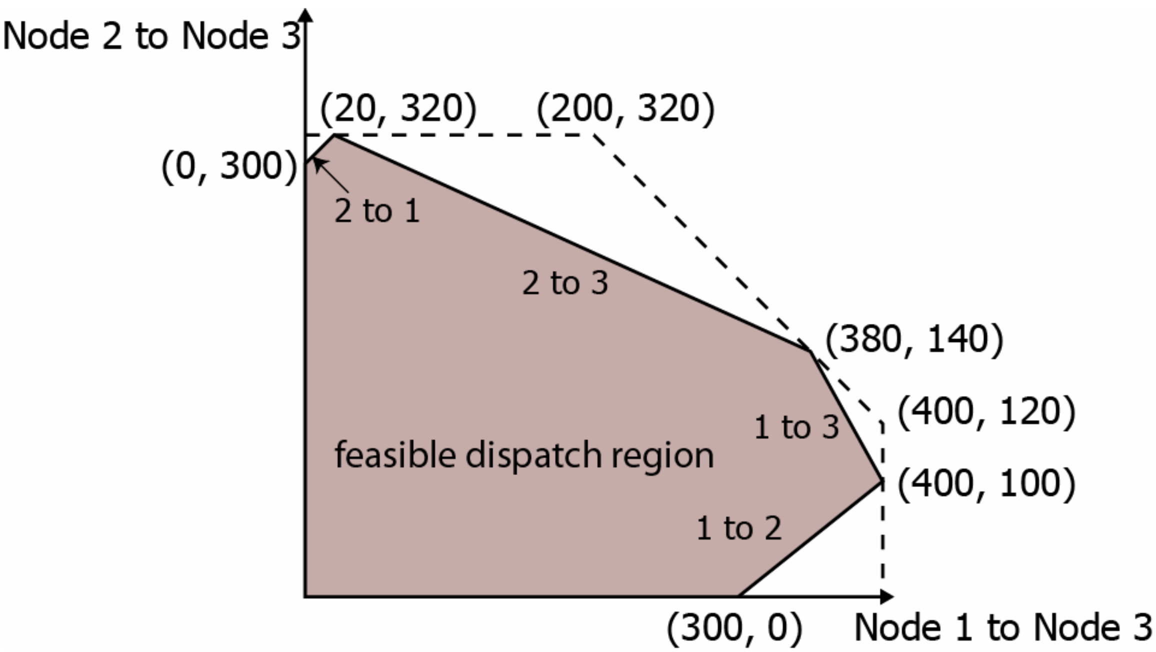


Figure 1-3 Nomogram of a Three-Node Example

A simple example shown in Figures 1-4 and 1-5 demonstrates how congestion might lower the inflow capability into California. The model comprises four areas: the western provinces of Canada, the Pacific Northwest, California, and the Southwest. In Figure 1-4 the flow and results using a transportation model are shown, and in Figure 1-5 the flows and results using a transmission model are shown. The line capacities into California from the Northwest and Southwest suggest a non-simultaneous total import capability of 17.3 MW. In both cases California is importing power along this path, but in the latter case the amount is much less, 5.3 GW instead of 9.9 GW. While the physical transmission lines between the Northwest and California may be able to support a 9.9 GW transfer limit, it is not possible to transfer more than 5.3 GW without exceeding the 1.8 GW limit set between the Northwest and Southwest. However, a power flow simulation of the generation costs at each node shown in the diagram result in an import capability to California of only 12.7 GW, 27% less. The importance of this effect is shown by the insert graphic in Figure 1-5. Because the supply in California is less than predicted by a transportation model, native production further on the supply curve resulting in higher prices and a better opportunity for EERE technologies to penetrate.

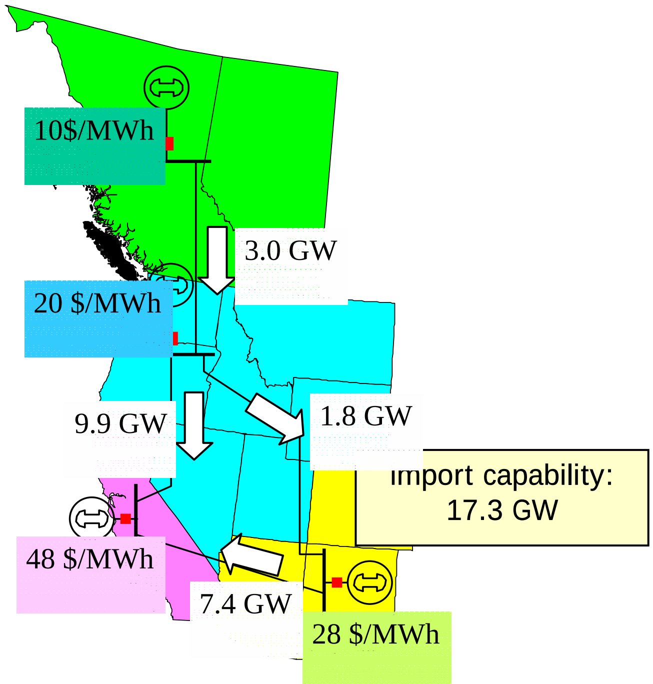


Figure 1-4 Four-Node Example Based on the WECC Region

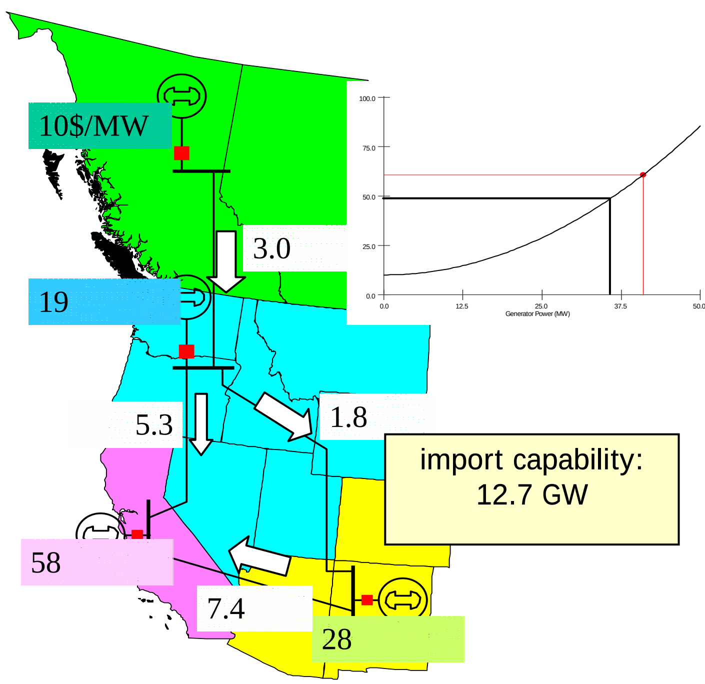


Figure 1-5 Four-Node Example Based on the WECC Region

1.3 Roadmap to this Report

The remaining sections of this report detail the steps of the process described above and report on the results and conclusions from this work. Section 2 explains the methods used to extract the merit dispatch order and to run it as a supply curve in a model consistent with LBNL-NEMS. Section 3 details the results that are drawn from an example case using this approach. Section 4 will draw conclusions from the example test case and Section 5 discusses the next steps to making this approach fully applicable for future work.

2. Developing an LBNL-NEMS Power Flow Layer

Presently, NEMS performs an economic dispatch that allows for beneficial trade between regions. In the NEMS transportation model framework, all line capacity combinations between regions are defined and they are assumed to constrain the system independently during the economic optimization. In practice, power flow between a pair of regions can be constrained by a limit set on flow between a different pair of regions, as explained above. In power system parlance, the initial power transmission capabilities between regions are called non-simultaneous capabilities, which represent the ability for power flow between these regions assuming all activity in other regions remains constant. When applied to the simultaneous case, these limits cannot be treated independently. This is where the transport model fails because it assumes that non-simultaneous transmission capabilities can be applied to the simultaneous case. This difference in capabilities is readily seen in the three-node example of the previous section and the nomogram shown in Figure 1-3. Unfortunately, this transportation model overestimates simultaneous transmission capacity, potentially resulting in a serious error.

A brief motivation for revising these models was provided in Section 1 for the Western Interconnect[4] using both a transport and so-called transmission model that includes a detailed power flow model. In that example, a clear economic difference is noted in the results between the two models. This section will explain an approach to testing the benefits of a transmission model in LBNL-NEMS by modifying the transport model limits to mimic those of a transmission model and incorporating simultaneous dependence. As discussed below, this approach is not perfect because it is not possible to force the transport model to exactly conform to a transmission model by simply adjusting the transport model capacity limits. But it does move the transport model results qualitatively in the right direction, and it serves the purpose of demonstrating differences between these models.

2.1 Developing an Aggregate Transmission Model to LBNL-NEMS Resolution

A power flow calculation requires two key sets of inputs, generator capabilities and costs to determine the optimal dispatch, and the transfer capabilities of the lines to determine the intertie flows that result from the optimal dispatch subject to the capacity of the system. The power flow results are generator outputs and prices at every node and transfers on all lines. Because LBNL-NEMS conducts its own isolated dispatch at each node based on the merit ordering of resources, this merit order is extracted from LBNL-NEMS for the exogenous power flow calculation. The summer and winter capabilities of the lines are provided by an input file and remain constant over time. Some code modifications were necessary to change these tie limits so that the resulting power flows could be reintroduced into LBNL-NEMS by the 36 time periods used to represent the year. LBNL-NEMS uses three time-of-day categories (midday, morning/evening, and night) to group the hours in a day. This grouping is applied to four seasons to comprise a total of 12 *groups*. Furthermore, each of the 12 groups is divided into three *segments* corresponding to the highest 1%, the next 33%, and the remaining 66% of the hourly loads in the group. Herein we will refer to the 36 combinations of groups and segments as *groupments*. For a detailed explanation, please see Appendix B. In other words, the modifications are twofold, one part being endogenous and the other exogenous. The endogenous part is that the transfer limits of the transportation model are

[4] The entire Western Interconnect is represented by the WECC NERC region.

refined to set limits that vary across the 36 groupments. The constraints for every groupment of every year come from the exogenous calculation. The exogenous part is that these transfer limits by groupment are chosen not based on the fixed transfer capability of the interties, but rather on a power flow conducted outside NEMS that uses the same merit order and physical grid representation. PowerWorld repeats thepower flow calculation for every groupment and all forecast years through 2025 based on the corresponding merit stack. If the expansion plan that LBNL-NEMS follows is changed in any run, this effect will be transferred to PowerWorld in the groupment merit stacks.

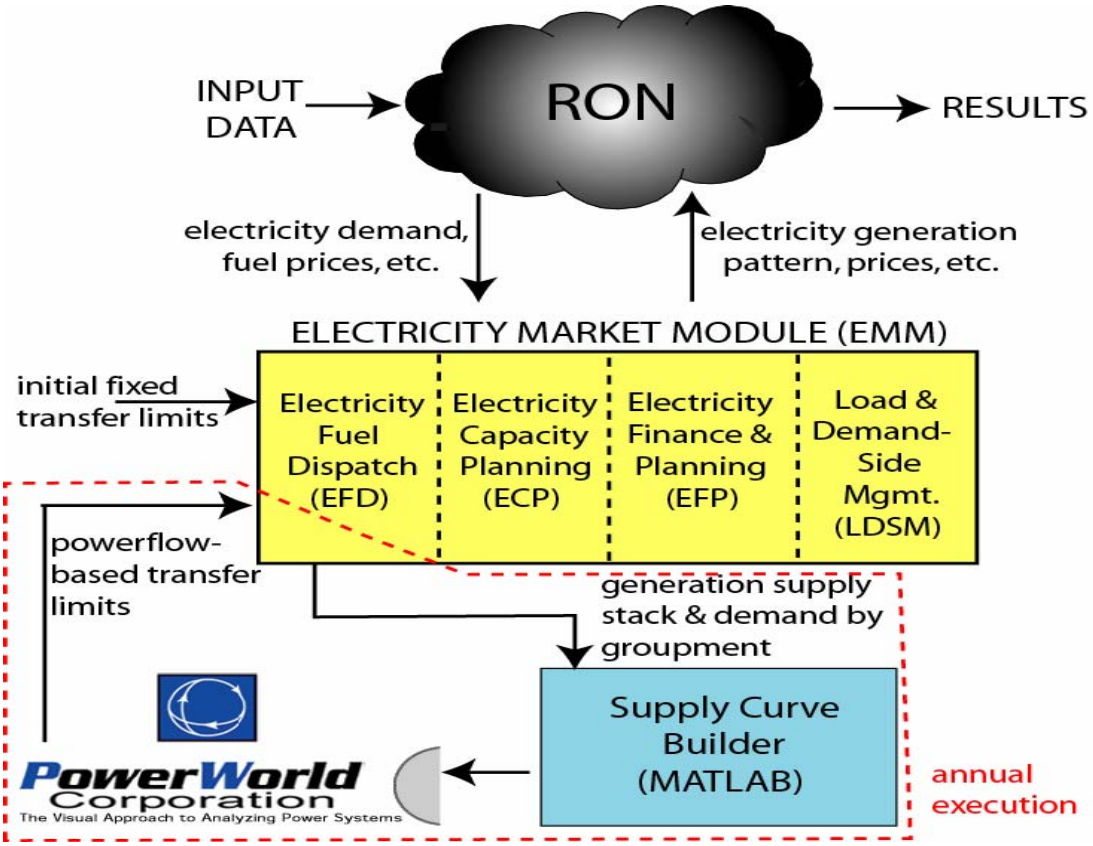


Figure 2-1 The RON Power Flow Model

Given the strict timeline associated with the GPRA analysis, the most useful enhancements to LBNL-NEMS are those that can be easily reimplemented annually with each new version of NEMS. To address this concern, the approach shown in Figure 2-1 has been developed. The schematic focuses on the Electricity Market Module (EMM) of NEMS, which deals with the expansion and operation of the power sector. The EMM itself consists of 4 submodules, the two most important of which are the Electricity Fuel Dispatch (EFD) that dispatches the existing system and the Electricity Capacity Planning (ECP), which decides how the system should be expanded to meet growing loads. All other modules of NEMS, called RON (rest of NEMS), are ignored. The goal is to make the minimal number of changes necessary such that the transportation model provides a better representation of the power flow in a system. In fact, the optimal power flow is run for the very same LBNL-NEMS-modified system using PowerWorld. An optimal power flow determines the least-cost economic dispatch to serve demand while accounting for generator costs, various constraints, and allowing for economic use of the transmission grid.

To model this effect in LBNL-NEMS, an optimal power flow model was developed with the granularity of the NEMS regions. The power flow transmission model was then solved with the path limits defined by the LBNL-NEMS data. The key difference is that the power flow correctly accounts for the dependence among paths and will not allow non-physical simultaneous flows that are allowed in the transportation model. Because the effects of power flow are overestimated, the original LBNL-NEMS limits are replaced with the actual flows from PowerWorld. An iterative procedure is applied: first the supply stack and load are extracted from the EMM and supplied to the power flow program. Second, the results of the power flow program are used to define the transfer limits in LBNL-NEMS. These two steps are iterated to achieve convergence.

In setting up the power flow case, certain data not available in LBNL-NEMS were required. Most importantly, electrical impedances between regions needed to be defined because it is not sufficient to have only the capacities defined between regions. This data was not available at the LBNL-NEMS scale.

Detailed electrical models for the Western and Eastern Interconnects and the Electric Reliability Council of Texas (ERCOT) region, as shown in Figure 2-2, were the starting point. The models were initially compiled from Federal Energy Regulatory Commission (FERC) data, and are similar to the data used to perform the detailed non-simultaneous transfer limit studies. The model for the Western Interconnect represents 13,653 nodes and 17,564 lines and transformers. The model for the Eastern Interconnect represents 33,538 nodes and 45,421 lines and transformers. The connections to ERCOT are identified and an ERCOT node is added to complete the model. The combination of the two models account for more than 45,000 nodes and 60,000 lines. In contrast, the LBNL-NEMS model consists of fewer than 30 regions and 60 connections. A challenge in this project was to aggregate this data from detailed models down to the coarse aggregate scale used by LBNL-NEMS, a process called *equivalencing*.

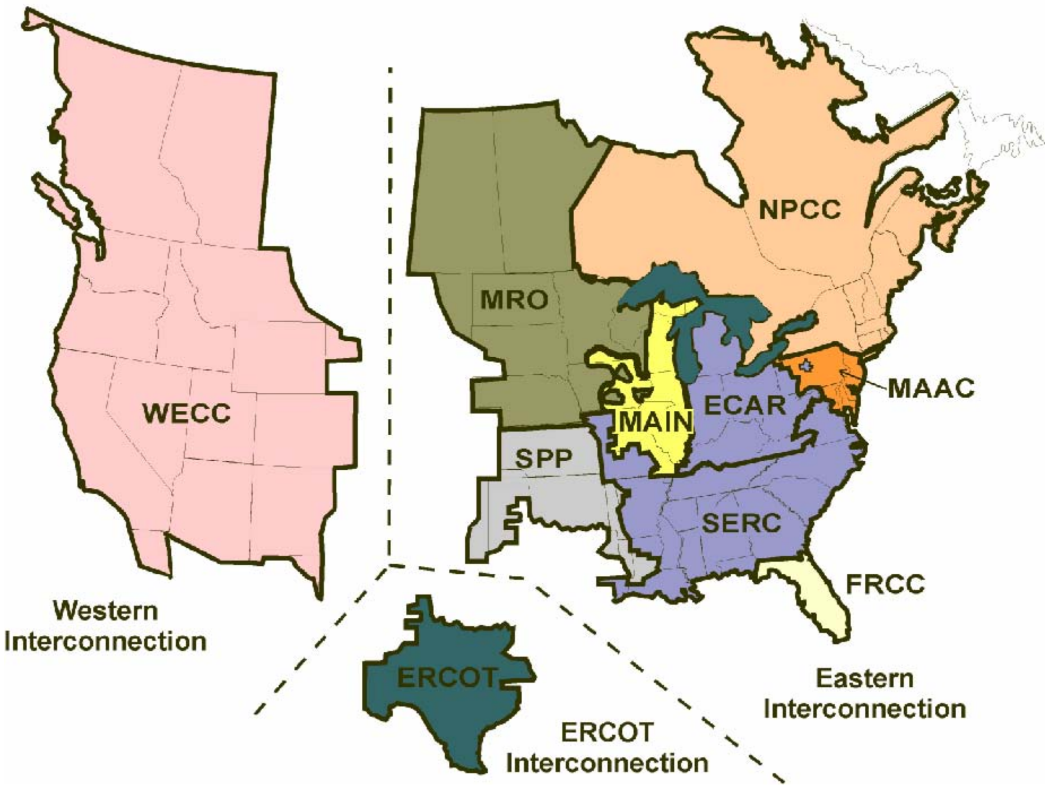


Figure 2-2 NERC Interconnection Map

The PowerWorld simulator was used for solving the commercial power flow. One of the key features of this simulator is an aggregation tool that allows users to retain nodes and then estimate an electrical equivalent that replaces the rest of the transmission grid. In this stage of the project, the aggregation tool was used to conform to the LBNL-NEMS-level of detail. Representative nodes were specified and PowerWorld calculated the impedances between them.

The choice of representative nodes deserves some discussion. Two approaches were evaluated, one of which was to assign the nodes with the largest capacity generators in each NEMS region and the other was to assign nodes as the largest loads in each NEMS region. Most of the resulting impedances of interest were similar in value between the two approaches, but some differed significantly. Consequently, the adopted implementation was an average of the two sets of impedances. Also, the model reduction results in connections between areas that are not represented in the LBNL-NEMS model. Because the LBNL-NEMS grid cannot be modified, the two models maintained a consistent structure, and the optimal power flow model was modified simply by removing the additional links.

In future work, the issue of model reduction should be revisited. There are a number of alternative ways this may be approached. This work is a proof-of-principle research that tests whether a plausible transmission model will alter the results obtained from the LBNL-NEMS transport model. This equivalencing process is explained in detail in Appendix A along with a discussion of alternative and possibly improved approaches for future research.

The impedances now defined between regions supply part of the network information needed to construct and run a power flow model. The additional information required are the demand and supply curves for each region, including the maximum capacity links between regions. These values are a function of year, group, and segment. The next section describes how these data are obtained from the NEMS data.

2.2 Extracting Load, Merit Stack, and Transmission Limits

NEMS calculates the power transfers between regions using a linear programming (LP) model based on the demand and generating capacities of power plants in each region. Other inputs to the LP include transfer limits and transmission costs between regions, renewable capacities in each region including Canadian imports. When solving for the transfer between regions during each groupment, the LP solves for all regions simultaneously. For this to work, the ordering of the groupments is assumed to be the same among all regions. For example, the peak segment for a summer midday in region 1 will coincide with the same peak segment of all other regions. This assumption that all regions will have their peak demands at the same group of hours does limit the ability of LBNL-NEMS to model interregional trade.

LBNL-NEMS determines if a plant is base load (always dispatched) by comparing the unit cost with the marginal cost of the LP solution. LBNL-NEMS also specified whether a plant is must-run or not. To provide inputs to PowerWorld, the following steps are introduced into LBNL-NEMS via code additions. For each groupment, the loads for each region in each year are retrieved into a file as well as the available capacities from power plants and renewables in each region and their associated cost. For base and must-run plants, the dispatched capacity is retrieved and for other plants, the available capacity is retrieved. From the extracted information, the must-run and renewable plants are grouped together and the remaining plants are sorted in ascending order of their costs to produce the supply curve needed for the PowerWorld analysis. The LBNL-NEMS transfer limits (non-simultaneous limits) between regions are also provided to PowerWorld.

2.3 Optimal Power Flow Solution Using PowerWorld

At this point, an electrical network representation for impedances between regions has been constructed while demand and supply curve information and maximum capacity limits between regions have been extracted. The next step is for PowerWorld to simulate the power flow.

This implementation makes use of two other features of PowerWorld. The first allows a base model to be modified by user-written auxiliary files. In this case the auxiliary files contain the specific information that is extracted from the LBNL-NEMS runs, that is the supply, demand, and transmission capacity information. The second feature is that PowerWorld can be opened and run from Matlab using PowerWorld's Simauto tool. For each year there are 36 power flows that need to be performed, one for each groupment. This is automated using a Matlab script that loads in the base model with the model structure and impedances, then it modifies the data using auxiliary files, and finally it writes the output of the model in a form that can later be used as input to the LBNL-NEMS runs. This script is presented in Appendix A.

2.4 New Transmission Limits used for LBNL-NEMS Runs

It is worth noting that the new transmission limits that come from the PowerWorld simulation for use in the LBNL-NEMS model are unidirectional. The power flow results show energy flowing from one region to another and there is no particular reason to specify bidirectional limits. Because LBNL-NEMS expects bidirectional limits, the reverse flow limit is set to zero.

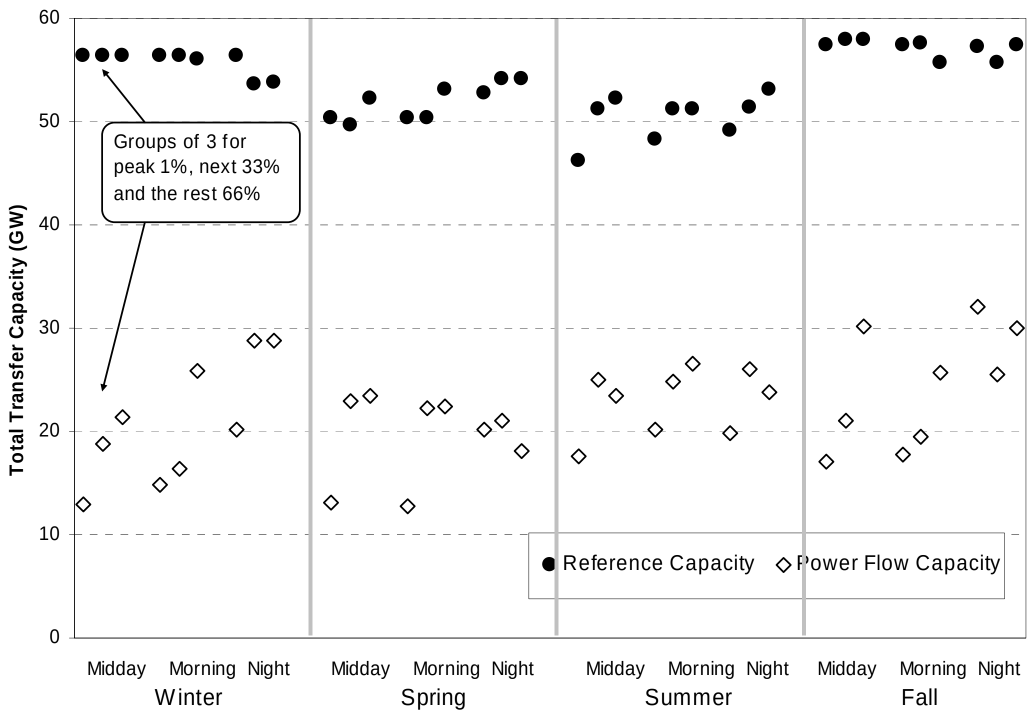


Figure 2-3 Total Simultaneous Unidirectional Transmission Capacity, by Groupment

The specified transmission capacity in the direction of the actual power flow is summed and compared for each groupment as shown in Figure 2-3 above. The limits based on the power flow studies are lower. This is consistent with the argument that not all of the non-simultaneous limits can be achieved simultaneously. Some links are effectively limited by constraints elsewhere.

Remember that this portion of the research was initially intended to limit the flows in the transport model that are not allowed in a power flow, so the transportation model mimics the results of a power flow model by adjusting the limits of the transportation model. Note however that the power flow model will allow flows that are not allowed in the transportation model. In an optimal economic dispatch, power can flow from a high-priced region to a low price-region, if this flow facilitates beneficial flow elsewhere. This is automatically accounted for in the power flow transmission model. A transport model does not allow power flow from a high-price region to a low region.

In the next section, the results of this study are presented, which include a comparison of LBNL-NEMS simulations with and without revised transmission limits using the power flow analysis. As will be discussed, the power flow-based limits do affect the results, but not dramatically. Instead, the dominant impact on long-term transmission usage appears to be due to fundamental assumptions about the location and availability of new generation capacity.

3. Results

There were four cases examined in this work:

- *Reference Case* – This case is similar to the AEO 2004 Reference Scenario except the transmission limits are defined for all 36 unique periods each year, where AEO only defines four sets of unique transmission limits each year to cover the 36 time periods for which the dispatch solves.
- *Power Flow Case* – This case has reduced transmission limits, which are explained in Section 2.
- *Doubled Case* – This case is just like the Reference Case except transmission grid grows over time to the point where the capacity is doubled by 2025.
- *No CaFl Coal Case* – This case is just like the Reference Case but coal builds are not allowed for the California and Florida regions.

3.1 Reference Case

The interregional economic trade in LBNL-NEMS stays pretty constant through 2009, then gradually declines by 25% by 2025 as shown in Figure 3-1. The fraction of total economic interregional trade relative to total domestic electricity sales is around 6% in 2005 and is predicted to drop to 3% by 2025.

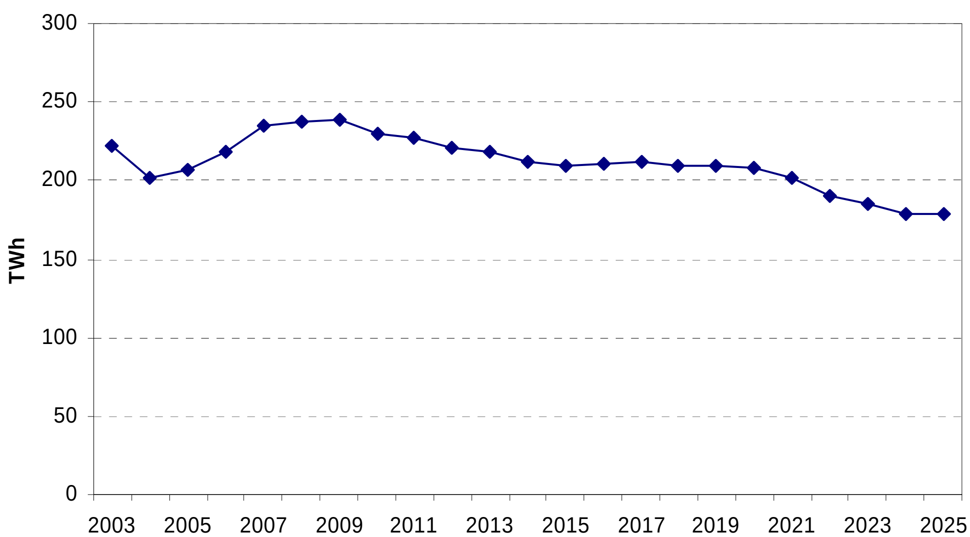


Figure 3-1 Reference Case Interregional Economic Electricity Trade Forecast

The absolute amount of trade, while important, does not directly relate to the amount of congestion. To measure congestion using LBNL-NEMS, Berkeley Lab calculates how close to capacity each transmission line is for every hour in a year. The total number of transmission lines between regions is 20, as shown in Figure 1-1, and the annual number of operating hours for each line is 8,760 hours. This amounts to 20 times 8,760 hours, or 175,200 line-hours every year. The level of congestion for each line and hour is characterized as either fully loaded, more than half full, less than half full, or completely unused. Figure 3-2 shows these measures of congestion in 2015 while Figure 3-3 shows the measures in 2025 for the Reference Case.

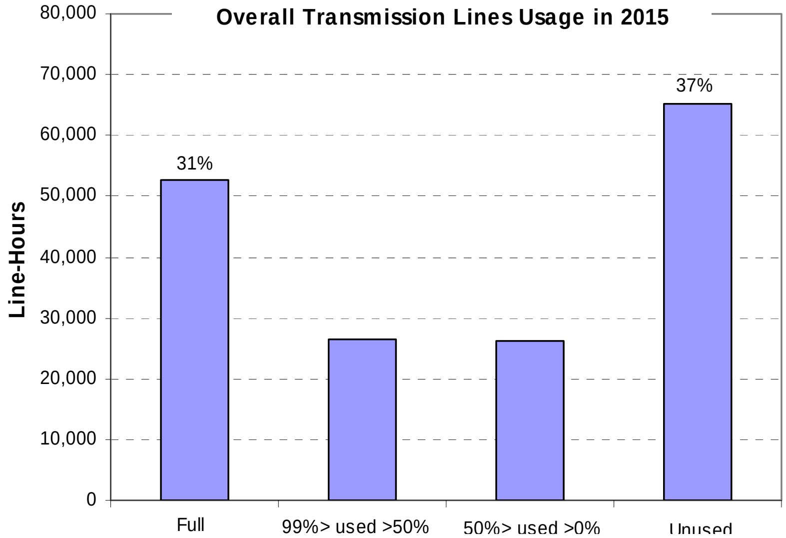


Figure 3-2 Congestion Reference Case, 2015

Interestingly, congestion by 2025 has abated from what it was in 2015. Although overall transmission usage falls over those ten years (Figure 3-1), it is not immediately intuitive that a one-third reduction in transfer would lead to a similar reduction in congestion (Figure 3-2 and Figure 3-3). After all, the congestion measure does not take into account that different lines have different capacities, and most of the transmission takes place on the largest lines, whether or not they are full. In the model, some of the transmission links that are congested are larger than 8 GW while some are as small as 150 MW. Therefore, the reduction in transmission could be much higher or lower than the reduction in congestion depending on what lines are affected.

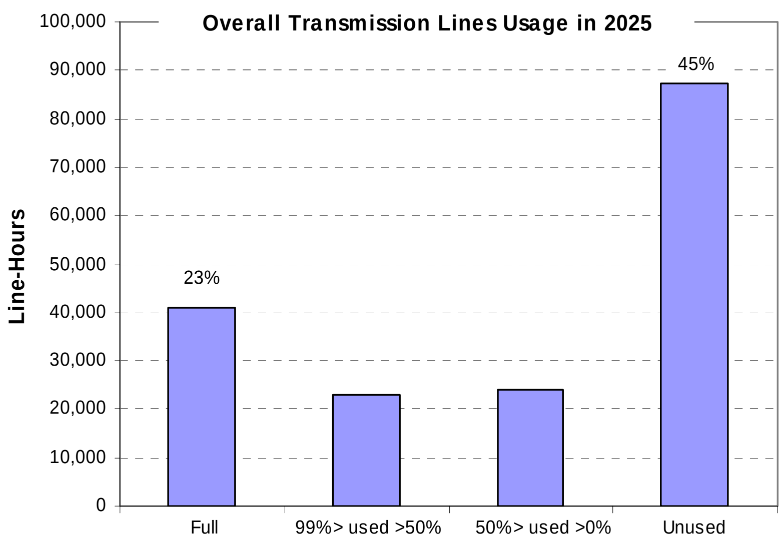


Figure 3-3 Congestion Reference Case, 2025

3.2 Power Flow Case

Introducing power flow should lead to different transmission patterns as the limits are changed dramatically. Specifically, the purpose of tightening the transfer limits in the Power Flow Case is to reduce the over-use of the transmission grid allowed by the transportation model. Figure 2-3 compares the limits in the two Cases across the 36 different groupments. The sums of limits on 20 interregional lines for each groupment are shown. Although the differences are quite significant when comparing these sums, the limit reduction on each individual line varies significantly. Some limits are not reduced at all and some are reduced by less than 1% of the original Reference Case value.

As expected, overall transmission is lowered in the Power Flow Case. Figure 3-4 shows that annual transmission is reduced by 15-30% from the Reference Case. In total, establishing a power flow layer in LBNL-NEMS reduced total simultaneous transfer capability by more than 50%. Figure 3-4 also shows a consistent gap of 45-75 TWh per year between the two cases. Both cases show a noticeable trend declining in overall transmission beginning around 2010. By 2025, the Power Flow Case results in only two-thirds the economic transmission it was in 2011.

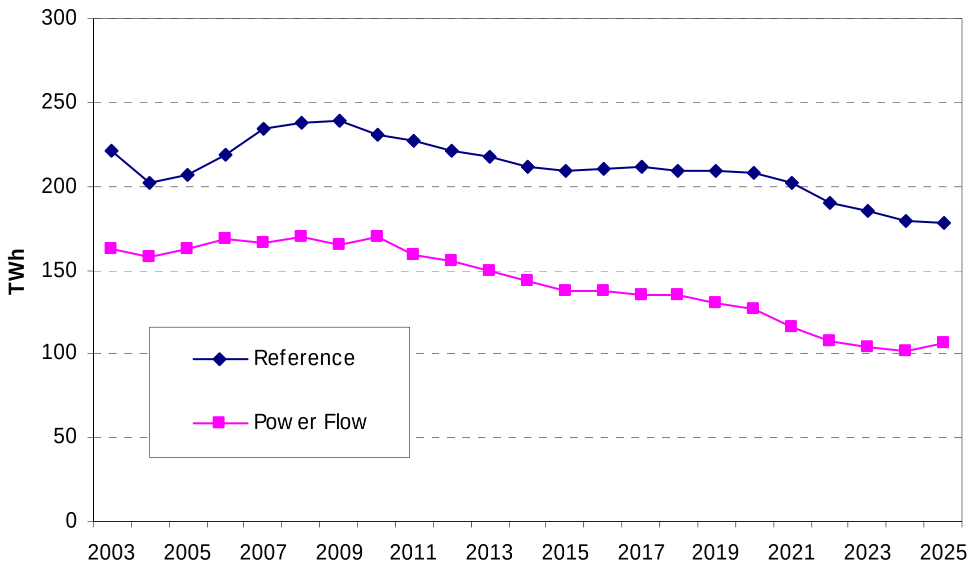


Figure 3-4 Economic Transmission in Reference and Power Flow Cases

Although LBNL-NEMS still uses a transportation model to determine transmission in the Power Flow Case, the imposed limits keeps simultaneous transfers within a realistic range. Figures 3-5 and 3-6 compare the total transmission against the total transfer limits for the Reference and Power Flow case respectively. The Reference Case has much higher limits than the Power Flow Case and also exhibits a wider gap between actual transmission and total capacity.

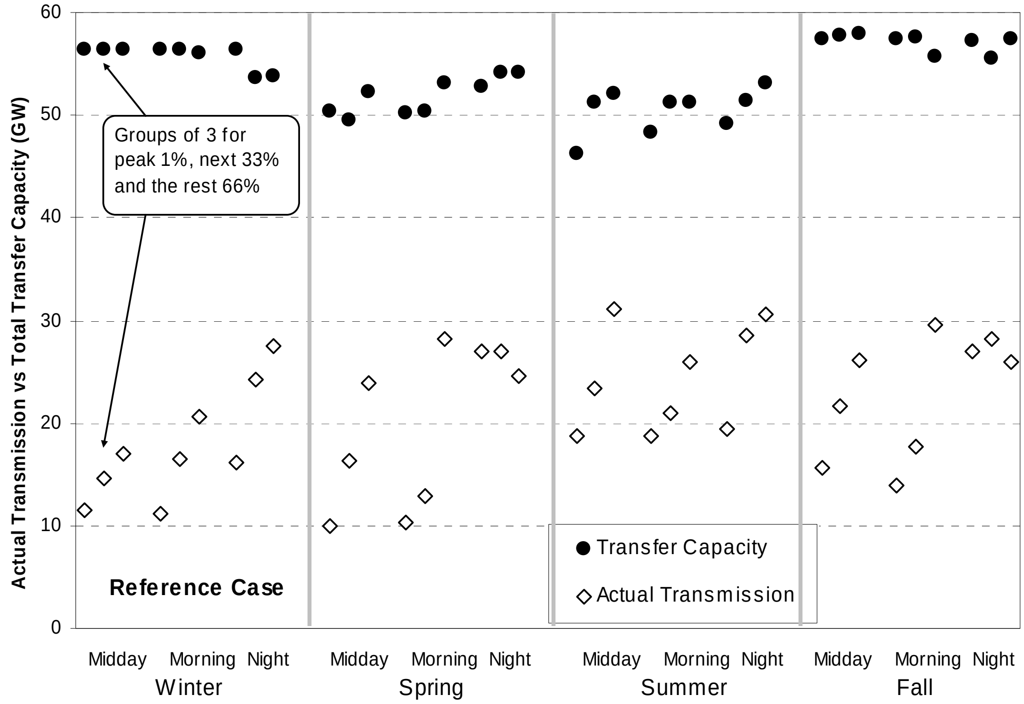


Figure 3-5 Actual Transmission and Transmission Capacity by Time Period, Reference Case, 2015

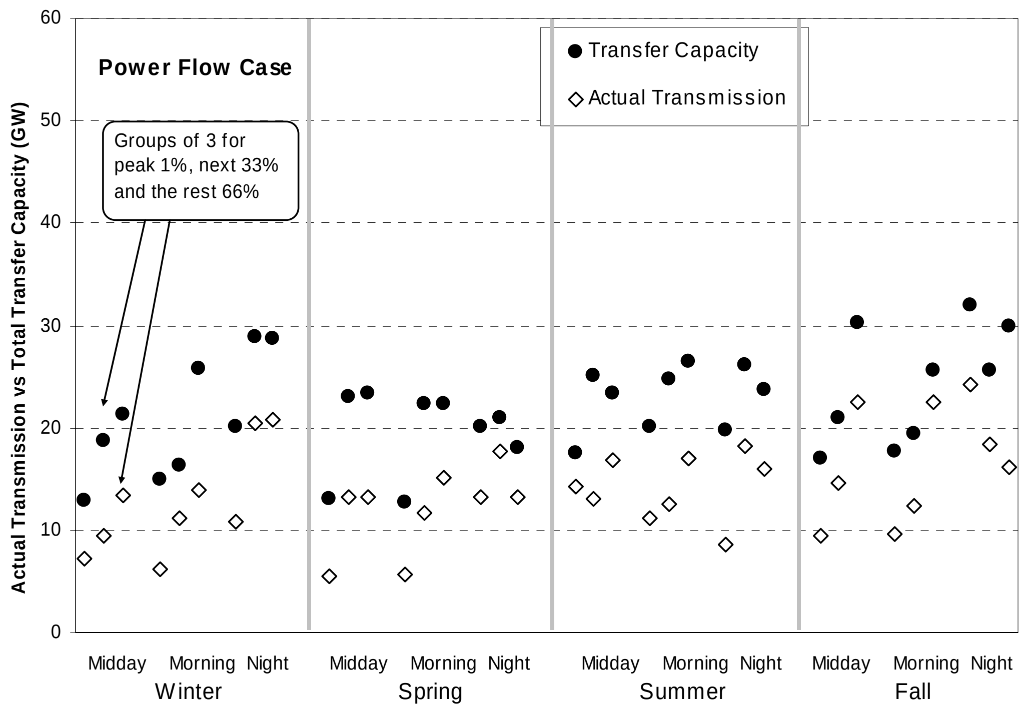


Figure 3-6 Actual Transmission and Transmission Capacity by Time Period, Power Flow Case, 2015

If the LBNL-NEMS simulation exactly mimicked the PowerWorld solution then congestion in the Power Flow Case would be close to 100%. Although LBNL-NEMS and PowerWorld use different solvers,[5] the tighter transmission limits do lead to more fully congested line-hours in the Power Flow Case than in the Reference Case. Furthermore, the reduction of congestion over time for the Power Flow Case is also much smaller. Between 2015 and 2025, full congestion goes from 40% to 37% (Figures 3-7 and 3-8).

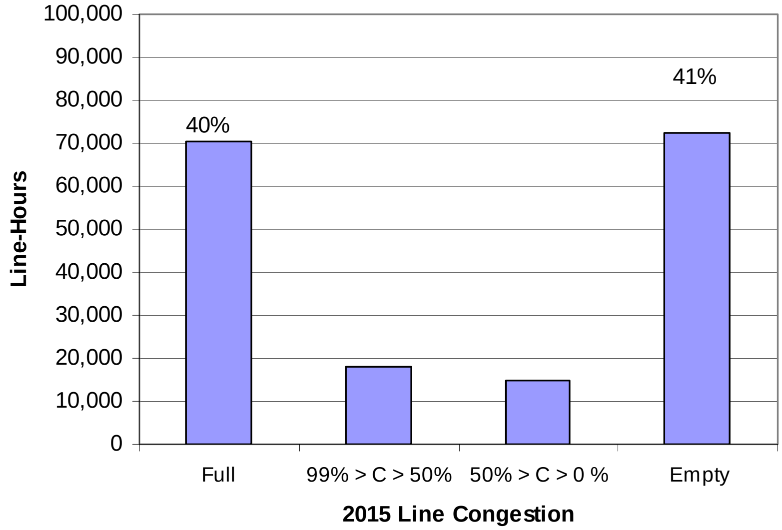


Figure 3-7 Congestion Power Flow Case, 2015

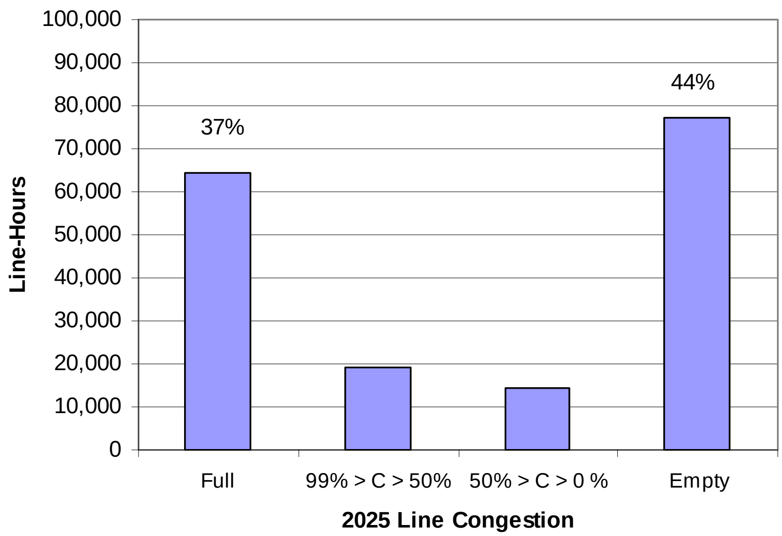


Figure 3-8 Congestion Power Flow Case, 2025

The Power Flow Case achieved its goals by proving that by the lowering the transfer limits, transfers are reduced and congestion is increased. However, these manipulations had only marginal effects. The most significant effect seems to be on renewable capacity growth, which

[5] In addition to the transportation model vs. transmission model differences, LBNL-NEMS includes transmission usage charges and imposes environmental constraints that are not represented in the PowerWorld calculation.

is still small as shown in Figure 3-9. However, because it showed the greatest impact, renewable capacity growth is evaluated throughout this report.

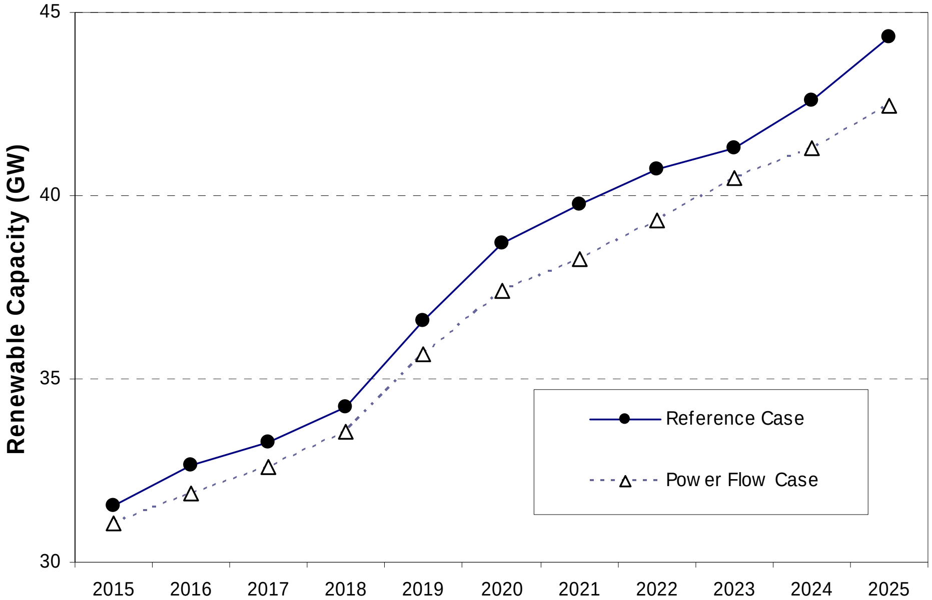


Figure 3-9 Renewable Capacity Reduction in Power Flow Case Relative to Reference

3.3 Doubled Transmission Case

Additionally, Berkeley Lab was also interested in modeling a congestion scenario whereby the transmission limits are doubled. This Doubled Case was expected to significantly reduce congestion and increase overall transmission seen relative to the Reference Case. Starting in 2016, the transmission limits are increased by 10% per year beyond the 2015 level and by 2025, the grid is 100% larger in the Doubled Case than in the Reference Case.

Modeling a larger transmission grid in the manner of the Doubled Case did not reveal much use of the extra capacity. This case forecasted a modest increase of up to 10% of overall transmission beyond that of the Reference Case as seen in Figure 3-10.

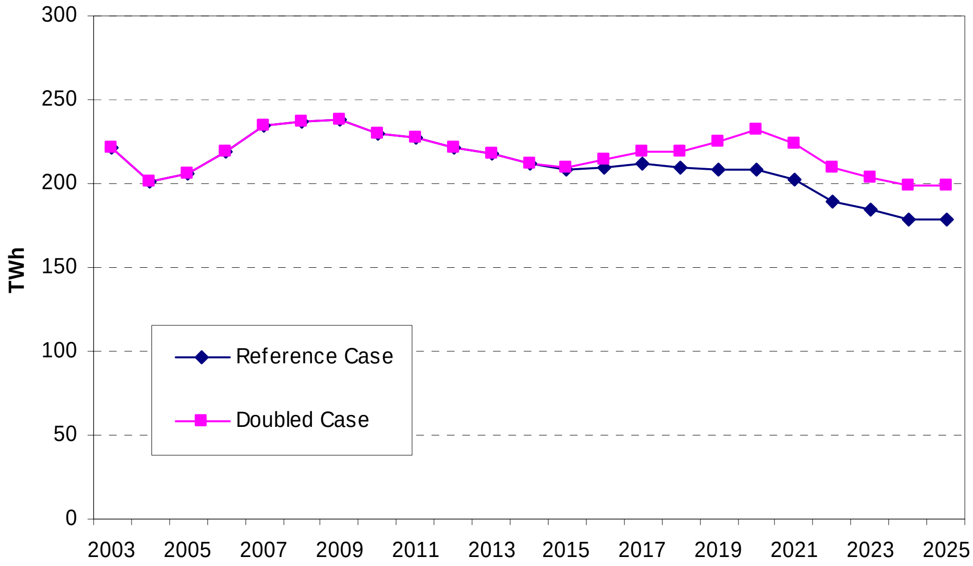


Figure 3-10 Economic Transmission in Reference and Doubled Cases

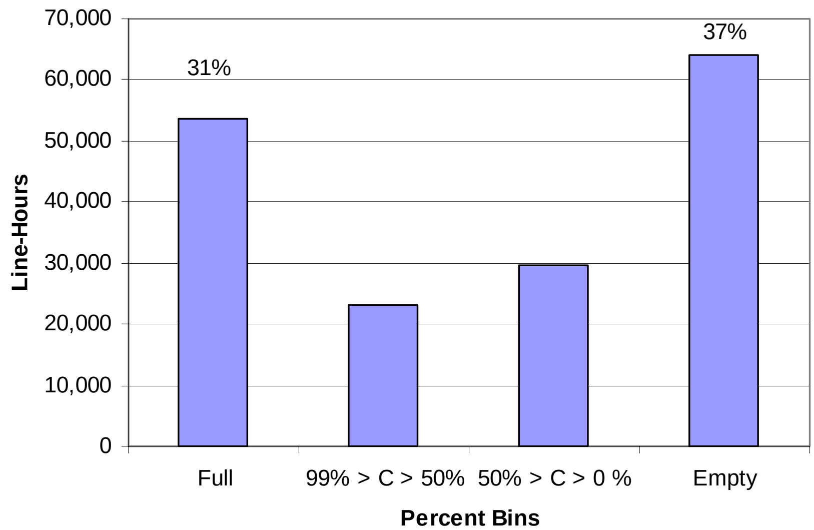


Figure 3-11 Congestion in Doubled Case, 2015

Congestion is reduced from 31% in 2015 (Figure 3-11) to 13% in 2025 (Figure 3-12). Of the 23% of line-hours congested in the Reference Case 2025 (Figure 3-3), the Doubled Case reduces congestion on almost half of those. However, as with the Power Flow Case, reducing congestion by doubling transmission does not result in other changes in the model forecast. The predominant effect on transmission still seems to be that exporting regions have less low priced capacity, while importing regions end up building new capacity close to load causing transmission to drop.

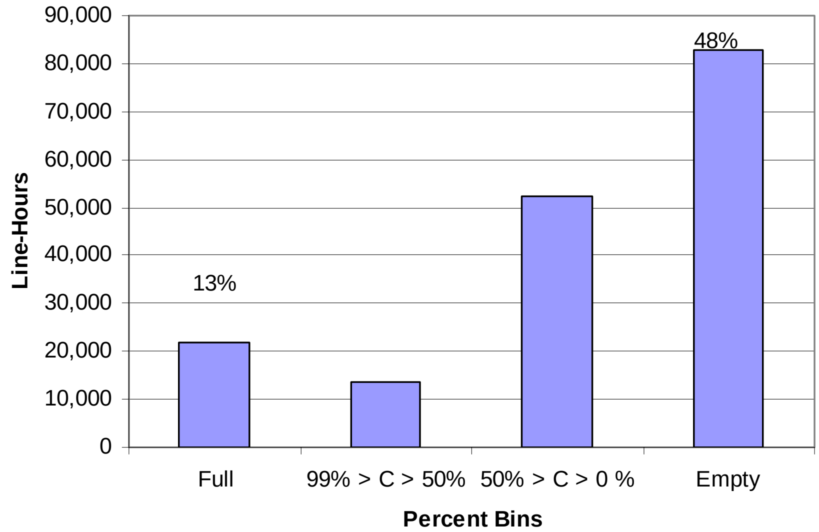


Figure 3-12 Congestion in Doubled Case, 2025

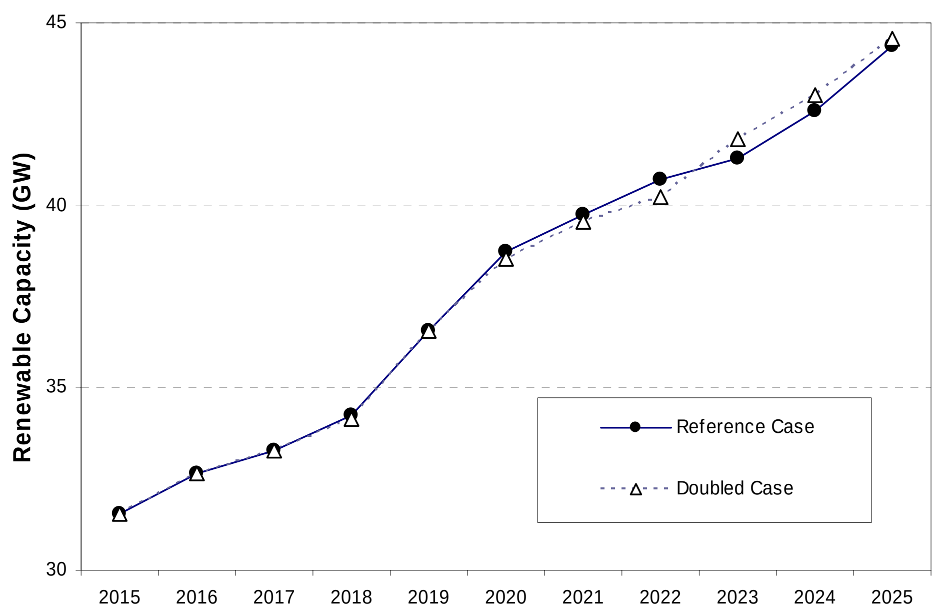


Figure 3-13 Renewable Capacity Forecast

Surprisingly, the Doubled Case is virtually identical to the Reference Case with no metric more than 1% different in 2025. For example, one of the GPRA metrics is renewable plant capacity change. Figure 3-13 shows the tiny variation to the renewable plant capacity forecast. Although the Doubled Case reveals a different electricity trading pattern, none of the standard metrics (i.e. carbon savings, oil consumption savings, electricity prices, natural gas consumption, total capacity, and energy expenses) are affected. Clearly, congestion is not a limiting constraint in LBNL-NEMS.

This conundrum led Berkeley Lab to confer with EIA about transmission in the model. Berkeley Lab learned that while reported transmission decreases, there is another sort of transmission that is unaccounted for in LBNL-NEMS. Natural gas plants can be built out of region for Florida and California with dedicated transmission. EIA designed the model to only allow these two regions to build out of region because they are aware of this sort of preexisting build pattern (Energy Information Administration 2005c). Additionally, new coal plants are not necessarily built in the region they serve. These plants are built with dedicated transmission capacity wherever the coal is. New coal capacity with dedicated transmission or unaccounted for transmission therefore make up what Berkeley Lab calls the *dedicated and detached grid*.

3.4 No CaFl Coal Case

In order to evaluate the dedicated and detached grid, a case was created where there is no coal plants built for California or Florida. The No CaFl Coal Case is the same as the Reference Case except that it is prohibitively expensive to build coal plants in other regions to serve California and Florida. In this case, total transmission levels flatten by 2015 instead of continuing to decline as it does in the Reference Case (Figure 3-14).

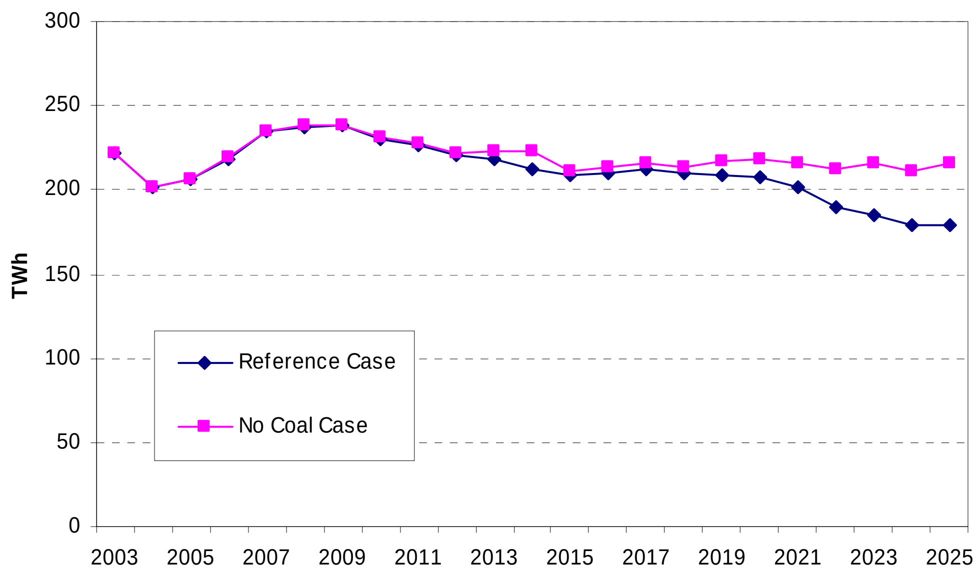


Figure 3-14 Economic Transmission in No CaFl Coal Case

About two-thirds of the additional transmission represents imports into California from the Northwest and Arizona/New Mexico (regions 11 and 12, Figure 1-1). Table 3-1 shows the amount of increased transmission into the California region. Marginal prices are also higher in the California region by 2025. Figure 3-16 compares marginal prices by groupment for the No CaFl Coal Case and Reference Case. The lowest marginal prices for California in the Reference Case are during the base load periods each season, where prices are usually under \$25 / MWh (2003 \$). Without the dedicated and detached grid serving California, marginal prices during the base periods usually exceed \$40 / MWh (2003 \$). LBNL-NEMS ends up with higher prices throughout the Western regions when new coal plants are restricted (see Figure 3-15).

Table 3-1 Additional Transmission to California in 2025, No CaFl Coal Case

In GWh	Reference	No CaFl Coal	Total Increase
From Region 11	33,864	47,397	13,533
From Region 12	0	10,751	10,751
Net	-	-	**24,284**

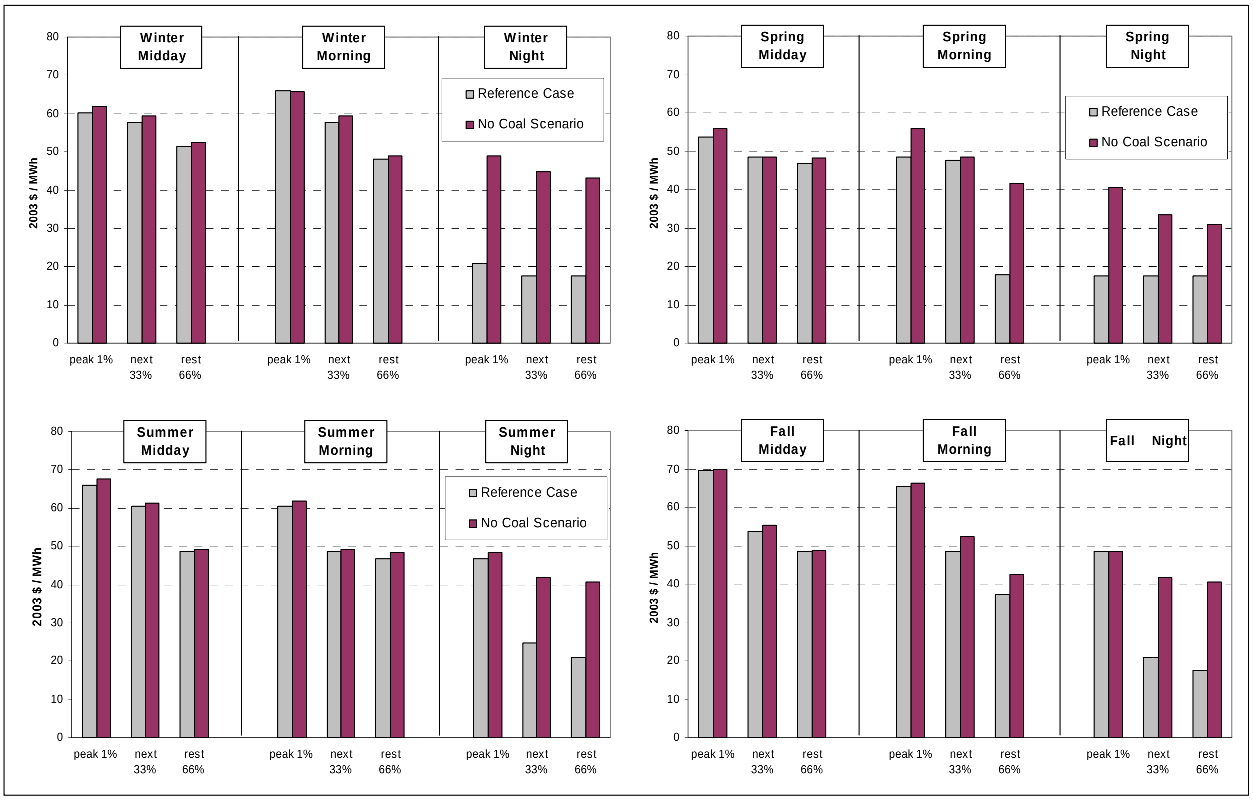
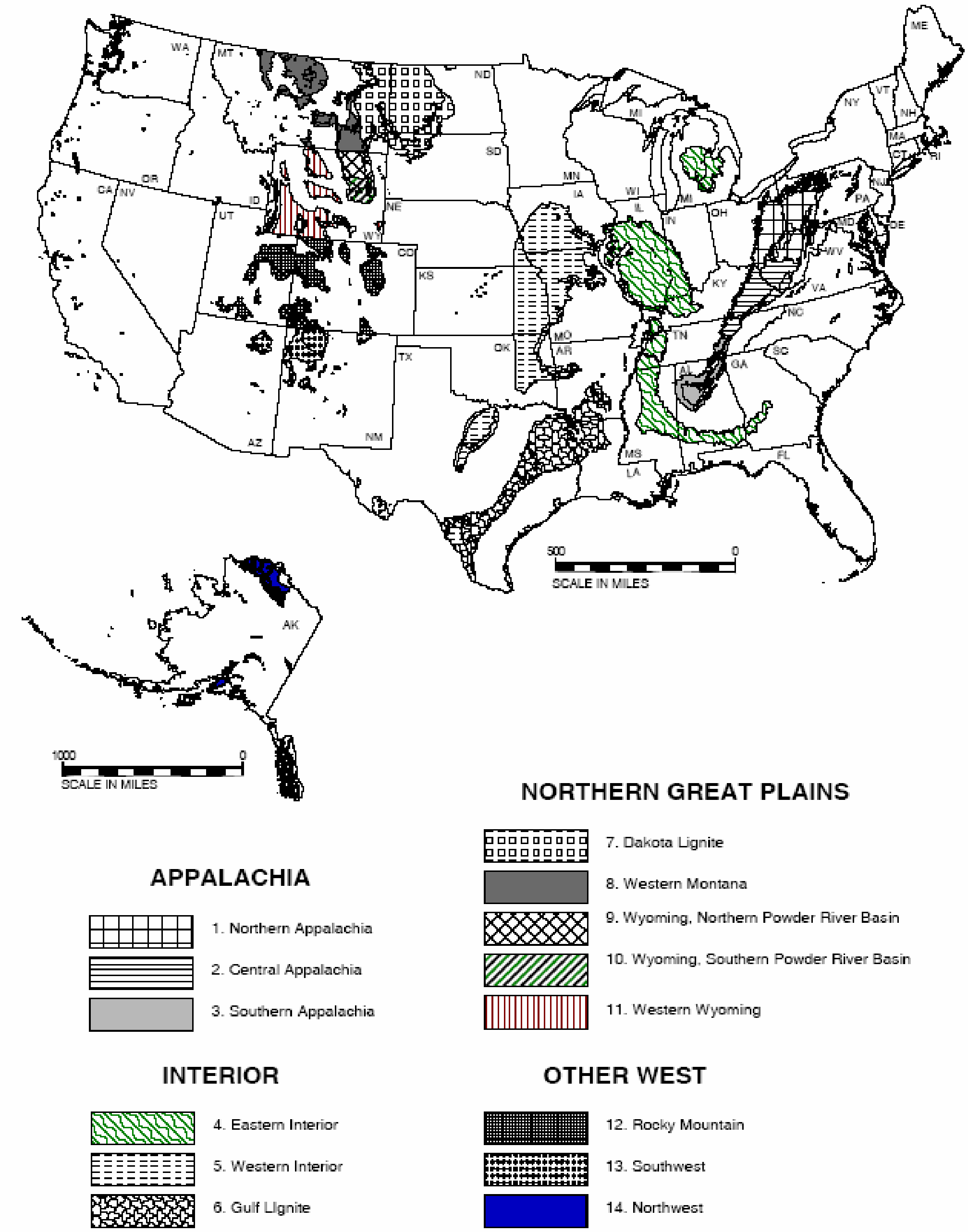


Figure 3-15 Region 13, California Marginal Prices in 2025, by Groupment

3.4.1 Coal Supply Regions and Electricity Market Regions

LBNL-NEMS allows coal plants to be built in any of the 13 electricity regions (Figure 1-1), based on where these regions buy coal, which are known as *coal regions*. Coal regions are shown in Figure 3-16. New coal plants are built with cost adders for transmission, or are located near the mines with dedicated transmission lines. For example, electricity region 13, California, for example, can build coal plants in coal region 12 Rocky Mountain (Utah/Colorado) or coal region 14 Northwest (Washington & Alaska). Since coal regions are not mapped onto electricity regions and some regions overlap it is hard to determine if new coal plants are physically in the electricity region to which they are dedicated.



source: (Energy Information Administration 2005a)

Figure 3-16 Coal Regions in NEMS

3.4.2 Additional Transmission and Congestion

Overall, congestion in the No CaFl Coal Case (Figures 3-17 and 3-18) is not much different than the Reference Case (Figures 3-2 and 3-3). There is slightly less congestion in 2015 and a little more congestion in 2025. However, evaluating congestion line-by-line reveals a compelling change. In the Reference Case in year 2025, the region 12 to 13 transmission line is never fully congested, while approximately 10% of the line-hours are full between region 11 and 13. In the No CaFl Coal Case, about 14% and 17% of line-hours respectively, are full. Merely, changing the capacity expansion logic for coal plants leads to a distinctly different transmission forecast. In other words, the No CaFl Coal Case reveals the existence of off-the-grid transmission between regions.

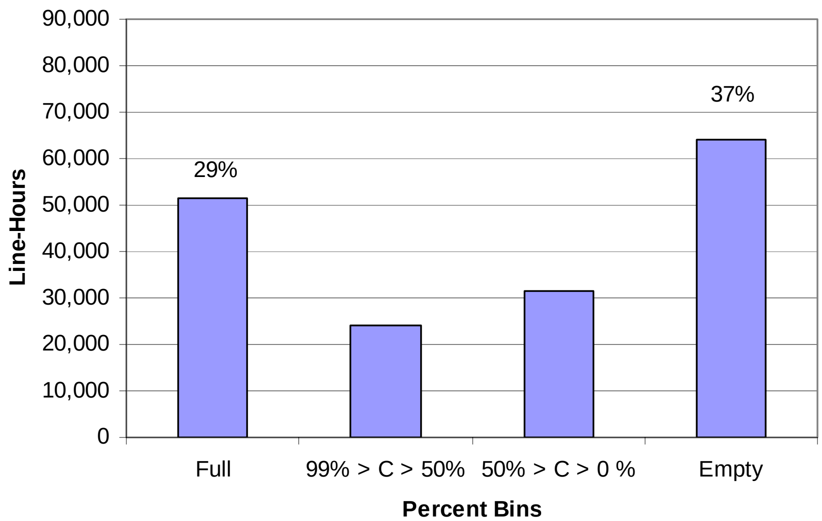


Figure 3-17 Congestion No CaFl Coal Case, 2015

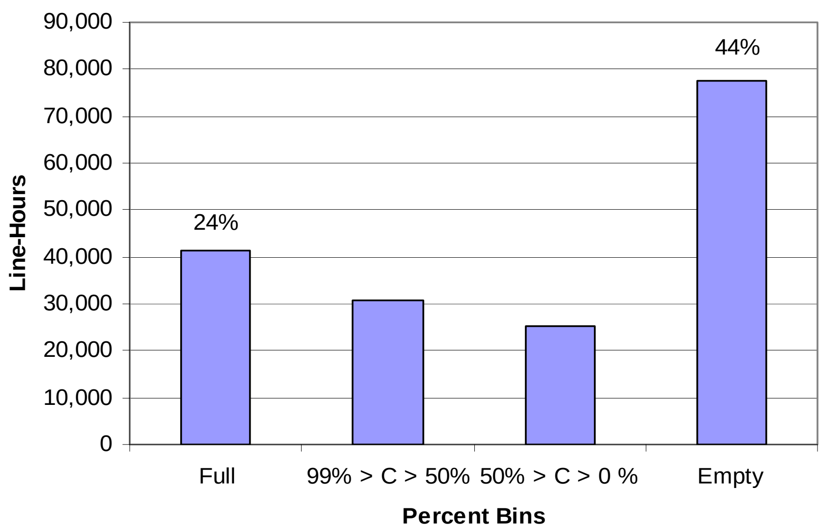


Figure 3-18 Congestion No CaFl Coal Case, 2025

The LBNL-NEMS results are so aggregated that the No CaFl Coal Case looks like the Reference Case in many ways. None of the parameters of interest (total energy consumption, carbon emissions, total generating capacity, non-renewable energy expenses, and electricity prices) distinguish themselves from the Reference Case even though the transmission and congestion patterns notably diverge. The growth of renewable generating capacity was perhaps most affected by coal capacity planning constraints (Figure 3-20), surpassing the Reference Case capacity by about 5%.

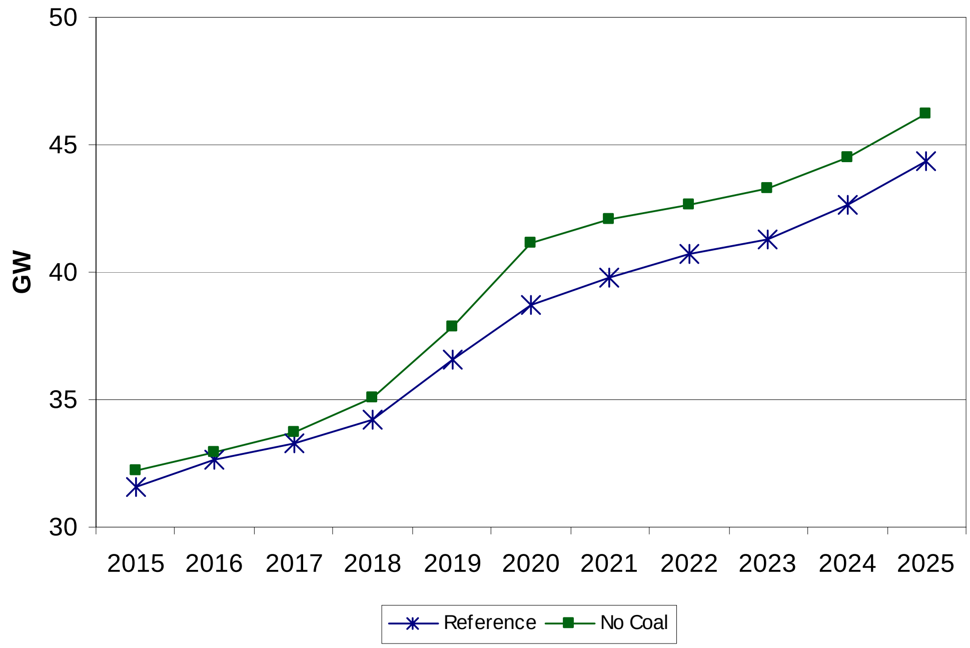


Figure 3-19 Renewable Capacity Forecast, No CaFl Coal and Reference Cases

The significance of this case is that LBNL-NEMS revealed another way that transmission may be underestimated. Alone, none of the underestimates that have been identified seem to have significant repercussions on the results. However, put together, the ways in which transmission is disfavored may easily obscure real pockets of opportunity for EERE technologies.

4. Conclusions

Understanding grid congestion is the key to understanding how and where electricity price differentials will develop and create niche opportunities for EERE technologies. However, there are multiple obstacles to using LBNL-NEMS for evaluating congestion on the grid. Without using an optimal power flow model, an overestimate of transmission capacity is likely.

4.1 Congestion is Reduced Over Time

This work demonstrated that the LBNL-NEMS modeling assumptions offset transmission bottleneck studies. Criteria for generation capacity expansion in LBNL-NEMS are primarily concerned with ensuring capacity to serve native regional load, and no concern is given to merchant builds that serve other regions. This has the unfortunate long term effect of de-emphasizing the need for transmission, and minimizing the ability to exploit beneficial regional trade that may be available.

All cases using LBNL-NEMS in this work showed transmission is reduced over time. While congestion exists, it is eroded over time. Neither increasing (Power Flow Case) nor decreasing (Doubled Case) congestion affected the results significantly. Berkeley Lab concluded that congestion becomes non-limiting by the end of the forecast. Therefore, aggregate prices, energy consumption, and new capacity do not change. The source of this effect in LBNL-NEMS seems to be that native generation growth reduces the need for transmission. Balancing native load growth and generation growth may seem most efficient path for future growth, but it may not be most realistic, based the obvious difficulties with siting new generation and transmission in densely populated areas. Moreover, recent history has shown growing congestion not less with increased merchant power plant construction.

4.2 Dedicated and Detached Grid

Part of the reason reported transmission is reduced over time is that the dedicated and detached grid hides transmission growth over time. The Reference Case has 222 GW of net capacity growth between 2004 and 2025 with at least 20% not a part of the transmission grid. In other words, over 46 GW of new capacity is transferred to a different region by way of the dedicated and detached grid. As a result, this portion of the capacity growth has no effect on the transmission grid or the congestion calculation. Table 4-1 refers to the electricity demand regions shown in Figure 1-1.

Table 4-1 Estimated Extent of Dedicated and Detached Grid

Demand Region	Number of New Plants	Generating Capacity	Type of Plants and Locations
NY (6)	15	7.2 GW	Coal built in ECAR (1) or MAAC (3)
FL (8)	14	15.7 GW	Coal built in SERC (9)
California (13)	17	14.9 GW	Coal built in NWP (11) and Rocky Mtn Ariz NM (12)
FL (8)	4	7.9 GW	Combined Cycle built in SERC (9)
Total	**50**	**45.7 GW**	

The estimate of the components of the dedicated and detached grid includes all out of region combined cycle generation that is built, as well as new coal plants built for regions that do not correspond to any coal region. This estimate may be an underestimate of new coal plants built out of region because the coal regions (Figure 3-16) and electricity regions (Figure 1-1) do not line up. For example, the Mid-Atlantic Area Council (MAAC) electricity region uses coal from the Appalachian. Clearly, these plants will either further constrain the existing transmission grid or will require expansion of the transmission grid. However, because transmission expansion is not explicitly modeled in LBNL-NEMS, it is difficult to assess the impact.

4.3 Power Flow Layer in LBNL-NEMS

Using a transmission model for solving the power flow instead of a transportation model was adequate, although without fully integrating the two models, the result was really a hybrid solution. Solving 36 time slices instead of two time slices each year, shows a wider range of power flow each year, however, until the model is sensitive to congestion, the wider effects of power flow in LBNL-NEMS will not provide an accurate depiction.

5. Challenges and Next Steps

Ultimately, Berkeley Lab hopes to quantify benefits of reliability by performing congestion sensitivity analysis using LBNL-NEMS. Many EERE technologies can benefit society by improving reliability or reducing congestion more so than by directly improving the traditional GPRA metrics. This report explains the first attempt to make the transmission grid forecast interregional transmission and the related congestion more realistically. However, in the course of this work it became clear that the potential economic benefits of transmission enhancement/lowering load are difficult to capture in light of other modeling constructs.

Therefore, before an appropriate metric for EERE technologies can be identified, the following steps should be taken:

- Reconsider the build logic in LBNL-NEMS that always puts new capacity where it is needed. The current logic to put new capacity next to the new load is an oversimplification which makes using the model to analyze congestion of marginal value. While it may be an ideal situation from the perspective of reducing reliance of the transmission grid, that logic is not necessarily consistent with economic-based decision making. The build routine should not be hardwired to force new generation at the load, but should allow distant generation to serve load when economically justified.
- Perform historical review of capacity growth along with an analysis of how new generation could be introduced into LBNL-NEMS that would take advantage of available transmission capacity.
- Allow the transmission grid to be expanded dynamically.
- The dedicated and detached grid in LBNL-NEMS should be combined with the traditional grid. Building a coal plant out of the region it is needed underestimates congestion and marginal prices. Either new generation would no longer be allowed to be built out of region as part of the dedicated and detached grid, or these plants would be welcome, and the new transmission capacity would be treated like the traditional transmission capacity.
- Remove the bias towards combine cycle and coal generation, which are the only types of generation currently allowed to be built out of region in LBNL-NEMS. Economics and other considerations and constraints should dictate the appropriate source of generation.
- A power flow layer should be embedded in LBNL-NEMS to appropriately limit transmission.

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Appendix A. Validating LBNL-NEMS Electricity Prices and Loads

A direct way to verify the accuracy of NEMS forecasting is to compare the forecasting data with the actual data. Most NEMS regions do not conform to actual pricing zones. But luckily, the boundary of New York Independent System Operator (NYISO) happens to be almost the same as the New York region in NEMS. Moreover, NYISO has a well functioning Locational Based Marginal Price (LBMP) based market with readily available pricing data. LBMP is defined as incremental system cost to provide the next unit of load, at a specific location in the grid. Due to congestion and transmission losses over the network, LBMP differs from zone to zone. It is comparable to the electricity price in NEMS because it is the market clearing wholesale price which the buyers pay to acquire electricity at a particular zone.

New York is divided to 11 zones. Its *Open Access Same-Time Information System* publishes LBMPs and load data daily by each zone. Weighted average LBMP by load of each zone is calculated for each of the NEMS' 36 segments (see Appendix B). These averages are used to represent the actual LBMP for the entire New York region and are compared with the corresponding inflation adjusted electricity prices of New York zone in 2004 from Reference Case. Figure A-1 shows great discrepancy between the forecasted electricity prices by LBNL-NEMS and the actual LBMP. Generally, the biggest differences come from segment 1 (top 1% of the hours in the group) of each group. For example, the weighted average LBMP of the top 1% of winter midday is almost 3 times the price from the Reference Case. In average, LBMP is about 1.4 times of the LBNL-NEMS prices. Also, actual LBMPs seem to have greater variations over different segments within the same group than the model's prices. Not surprisingly, price spikes do not result from LBNL-NEMS forecasting. Notably though, the same situation does not hold for the load data. The Reference Case load data for 2004, seen in Figure A-2, matches very well with the actual load reported by the NYISO. In fact, this is a well known characteristic of NEMS generally. It forecasts quantities reasonably well, but not prices.

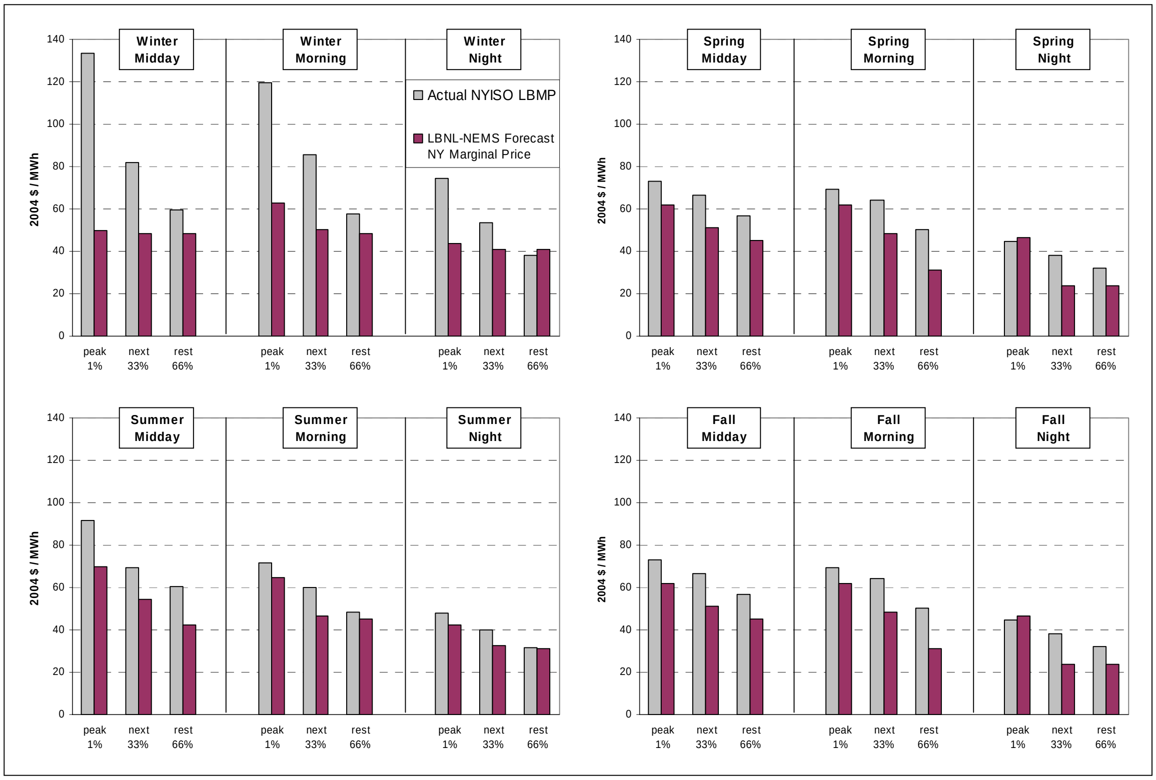

Figure A-1 NYISO Weighted Average 2004 LBMP Compared with LBNL-NEMS Forecasted Marginal Prices

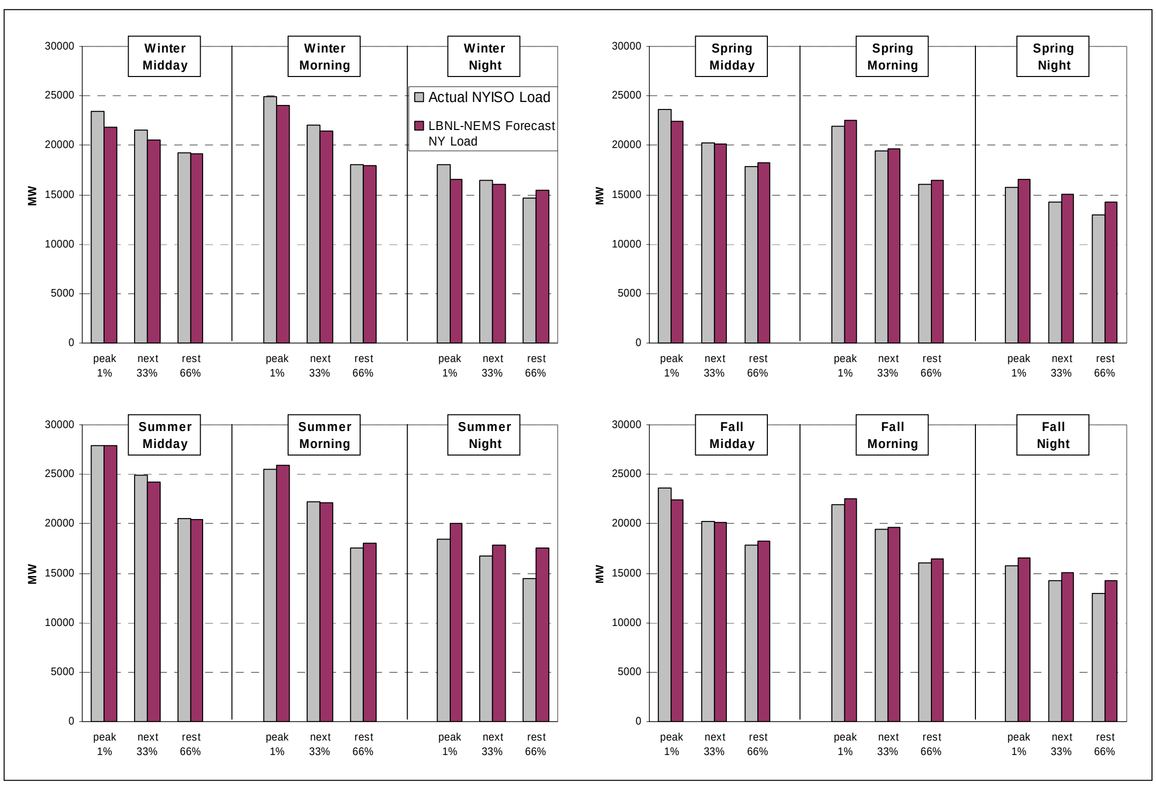

Figure A-2 NYISO 2004 Actual Load Compared with LBNL-NEMS's Forecasted NY Load

Appendix B. Definition of Groups and Segments in NEMS

In the Electricity Fuel Dispatch submodule of NEMS, the hourly loads are classified into 12 groups and then broken down further into 3 segments within each group. The 36 combinations of groups and segments are referred to as groupments.

Groups

The 12 groups correspond to a combination of 4 seasons and 3 time-of-day periods.

Seasons

Season 1 - Winter	(Dec/Jan/Feb	total 90 days)
Season 2 - Spring	(Mar/Apr/May	total 92 days)
Season 3 - Summer	(Jun/Jul/Aug	total 92 days)
Season 4 - Fall	(Sep/Oct/Nov	total 91 days)

Time-of-day periods

1 - Midday

Winter/Spring	8 hours	(0900-1600)
Summer	11 hours	(0800-1800)
Fall	10 hours	(0800-1700)

2 - Morn/Evening

Winter/Spring	11 hours	(0600-0800, 1700-2400)
Summer	8 hours	(0600-0700, 1900-2400)
Fall	9 hours	(0600-0700, 1800-2400)

3 - Night

Winter/Spring	5 hours	(0100-0500)
Summer	5 hours	(0100-0500)
Fall	5 hours	(0100-0500)

The 12 groups are:

	Group	# hours in a day	# of days	Total # of hours
1	Winter midday	8	90	720
2	Winter morning/evening	11	90	990
3	Winter night	5	90	450
4	Spring midday	8	92	736
5	Spring morning/evening	11	92	1012
6	Spring night	5	92	460
7	Summer midday	11	92	1012
8	Summer morning/evening	8	92	736
9	Summer night	5	92	460
10	Fall midday	10	91	910
11	Fall morning/evening	9	91	819
12	Fall night	5	91	455
Total				8760

Segments

Within each group, three segments are defined, after ranking the hourly demands from high to low.

Segment 1 - top 1% of the hours in a group
Segment 2 - next 33% of the hours in a group
Segment 3 - remaining 66% of the hours in a group

Groupments

Groupment 1 – Winter midday, top 1%
Groupment 2 – Winter midday, next 33%
Groupment 3 – Winter midday, last 66%
Groupment 4 – Winter morning/evening, top 1%
Groupment 5 – Winter morning/evening, next 33%
Groupment 6 – Winter morning/evening, last 66%
Groupment 7 – Winter night, top 1%
Groupment 8 – Winter night, next 33%
Groupment 9 – Winter night, last 66%

Groupment 10 – Spring midday, top 1%
Groupment 11 – Spring midday, next 33%
Groupment 12 – Spring midday, last 66%
Groupment 13 – Spring morning/evening, top 1%
Groupment 14 – Spring morning/evening, next 33%
Groupment 15 – Spring morning/evening, last 66%
Groupment 16 – Spring night, top 1%
Groupment 17 – Spring night, next 33%
Groupment 18 – Spring night, last 66%

Groupment 19 – Summer midday, top 1%
Groupment 20 – Summer midday, next 33%
Groupment 21 – Summer midday, last 66%
Groupment 22 – Summer morning/evening, top 1%
Groupment 23 – Summer morning/evening, next 33%
Groupment 24 – Summer morning/evening, last 66%
Groupment 25 – Summer night, top 1%
Groupment 26 – Summer night, next 33%
Groupment 27 – Summer night, last 66%

Groupment 28 – Fall midday, top 1%
Groupment 29 – Fall midday, next 33%
Groupment 30 – Fall midday, last 66%
Groupment 31 – Fall morning/evening, top 1%
Groupment 32 – Fall morning/evening, next 33%
Groupment 33 – Fall morning/evening, last 66%
Groupment 34 – Fall night, top 1%
Groupment 35 – Fall night, next 33%
Groupment 36 – Fall night, last 66%

Appendix C. Additions and modifications to LBNL-NEMS

The transfer limits are originally defined by seasons only and are stored in the variable CNSTRNTS. The variable CNSTRNTS is replaced by a new variable LBLcnstr which stores the transfer limits by groups and segments. In NEMS, the transfer limits can vary only among 4 seasons. LBNL-NEMS has been modified so that the limits can change in each of the 36 different groupments.

Codes are added to the EDF submodule of LBNL-NEMS to output each year, for each groupment, the loads in each EMM region as well as the power plant capacities and their costs. NEMS makes a distinction between base/intermediate load plants and peak plants, so that certain plants, like coal plants, are only allowed to run for base/intermediate loads and not for peak loads. For the cycling with PowerWorld however, the plants were not separated into two supply curves. NEMS also identifies if a plant is a must-run or not.

A separate program post-processes the file containing the outputted information. It first combines the must-runs and renewables together, then sorts the rest of the plants by cost to form the supply curve. The program merges the regional loads, the supply curve and the transfer limits (*ettin.txt*) into the auxiliary files that are used by PowerWorld.

After PowerWorld is run, the transfers between regions by each groupment are extracted and written to files for each year. Those files are then merged into an input file *ettin_iter1.txt* as the new transfer limits to be used by LBNL-NEMS. The model is rerun with the new transfer limits (read into the variable LBLcnstr). Afterwards, new auxiliary files with regional loads and supply curves are then produced and used in the next iteration of PowerWorld.

After the second iteration of PowerWorld, the transfers are again written to files. The new transfer limits are averaged with the transfer limits from the previous PowerWord run (*ettin_iter1.txt*) to produce a new input file *ettin_iter2.txt* to be used by LBNL-NEMS. This iterative process between LBNL-NEMS and PowerWorld is done three times.

Appendix D. Network Equivalencing

This is a brief description of the network equivalencing procedure used to reduce the original model of the Nation's electric grid of over 60,000 nodes down to fewer than 30. A feature of PowerWorld is employed to performs this calculation, and from the documentation it appears that it is a reduction based on systems bus-admittance matrix.

The relation between injected bus currents and bus voltages is linear:

$$I = YV$$

where I is a vector of injected currents, V is a vector of bus voltages, and Y is an admittance matrix relating the two quantities. Furthermore, in this case, the goal is to simplify the representation to use a single representative bus for an entire NEMS region, and so, accordingly, one node in each region is chosen to serve this purpose. Then the vectors and the matrix can be reordered to take the following form:

$$\begin{bmatrix} I_{NEMS} \\ I_{rest} \end{bmatrix} = \begin{bmatrix} Y_A & Y_B \\ Y_C & Y_D \end{bmatrix} \begin{bmatrix} V_{NEMS} \\ V_{rest} \end{bmatrix}$$

In the resolution of our LBNL-NEMS application, all generation and all demand are modeled at a single node, and in the equation above, $I_{rest}=0$. The resulting simplified model is given by

$$I_{NEMS} = [Y_A - Y_B Y_D^{-1} Y_C] V_{NEMS} = Y_{NEMS} V_{NEMS}$$

from which the resulting impedances can be extracted from Y_{NEMS}. This procedure is automatically done by PowerWorld. (Alternative methods are possible, which are discussed at the end of this appendix.)

To follow this procedure, representative buses need to be defined for the NEMS regions. First, both the location of the largest generator in each region, and the location of the largest load were examined. Then the impedances resulting from these two approaches were averaged for use in the power flow calculations. There are two other issues that require mention. First, the Interconnects and ERCOT are separated by DC lines. To piece together a complete model for LBNL-NEMS, the buses in the network at the terminals of the DC lines connecting the Interconnects were retained, and small nominal impedance between them was assumed. Second, the reduction procedure provided equivalent impedances between all the NEMS regions. NEMS does not accommodate all these connections. Those that are not in the NEMS model were removed from the power flow model.

The resulting reactances are listed in Table D- 1. Some of the reactances are calculated between NEMS regions and nodes connecting the three distinct Interconnects. The absolute values of these reactances are not important, their sizes relative to each other dictate the high and load impedance paths.

Table D- 1 Electrical Reactances Used in Power Flow

From Number	From Name	To Number	To Name	X
1	ECAR	4	MAIN	0.141
1	ECAR	9	STV	0.128
1	ECAR	19	ONTcan	0.189

2	ERCOT	2206	ECRNS	0.1
2	ERCOT	2207	ECRES	0.1
3	MAAC	1	ECAR	0.127
3	MAAC	9	STV	0.227
4	MAIN	5	MAPP	0.283
4	MAIN	10	SPP	0.138
5	MAPP	18	MANcan	0.294
6	NY	3	MAAC	0.11
6	NY	19	ONTcan	0.201
6	NY	20	QUEcan	0.069
7	NE	6	NY	0.297
7	NE	20	QUEcan	0.063
9	STV	4	MAIN	0.116
9	STV	5	MAPP	0.636
9	STV	8	FRCC	0.108
9	STV	10	SPP	0.337
10	SPP	5	MAPP	0.352
10	SPP	1101	WSC1E	1.915
10	SPP	1102	WSC2E	4.676
10	SPP	2106	ECRNN	0.273
10	SPP	2107	ECREN	0.257
11	NWP	17	BCcan	0.084
11	NWP	1204	WSC4W	0.336
12	RA	11	NWP	0.341
12	RA	13	CA	0.071
12	RA	1205	WSC5W	0.317
13	CA	11	NWP	0.218
17	BCcan	23	ALBcan	0.251
19	ONTcan	5	MAPP	0.822
21	MARcan	7	NE	0.393
24	MEX	13	CA	0.201
1101	WSC1E	1102	WSC2E	0.08
1101	WSC1E	1201	WSC1W	0.001
1102	WSC2E	1202	WSC2W	0.001
1103	WSC3E	5	MAPP	0.58
1103	WSC3E	1105	WSC5E	0.056
1103	WSC3E	1203	WSC3W	0.001
1104	WSC4E	5	MAPP	0.487
1104	WSC4E	1204	WSC4W	0.001
1105	WSC5E	1205	WSC5W	0.001
1201	WSC1W	12	RA	0.36
1202	WSC2W	12	RA	0.363
1203	WSC3W	1205	WSC5W	0.066
2106	ECRNN	2107	ECREN	0.203
2106	ECRNN	2206	ECRNS	0.001
2107	ECREN	2207	ECRES	0.001

This equivalencing procedure provides plausible values for impedances to use in a power flow study for the initial study. In the future a more detailed equivalencing procedure is warranted. One may choose, for instance, to represent more nodes within a region to better represent some geographic distribution of generation and loads. It would be sensible to retain buses at the edge of each region to ensure that the interfaces match the connections used in the NEMS model.

Appendix E. Matlab Script and Sample Auxiliary File

This section presents the matlab script that runs the power flow solver and writes out new transmission capacity limits for LBNL-NEMS. An abridged version of an auxiliary file follows, in order to show its structure.

Matlab Script

```
% this is the main routine for using matlab to operate PowerWorld
% for the PBA project.
% Outline:
%   0.  set up outer loop to step through years and slices
%   1.  Load in predefined auxiliary files
%   2.  Run PowerWorld
%   3.  Extract and save data.

%% SET UP CONNECTION WITH POWERWORLD
A = actxserver('pwrworld.simulatorauto');
%% function call follow the form
%% output = A.SomeFunction(parameters);
%% No optional parameters are allowed.  We'll if this matters for our
%% functions.

% open case
output = A.OpenCase('c:\BCLDATA\PBFA\PBFA 2004\Equivalents\Y14matlab\Y14base.pwb');
if~(strcmp(output{1},''))
   disp(output{1})
else
   disp('Open Case successful')
end
clear output;

%%%% Open outputfile
fout = fopen('newlimits','w');
fprintf(fout,'ID\tfrom\tto');


%% SET INTERFACE
%% convert between interface ID in data to Interface ID in PowerWorld.
[convA convB] = xlsread('Y14Data/Interfaceconversion.xls');
convB = convB(2:end,3);
numberofconstraints = size(convA,1);


%0.  Outer Loop
for year = 1995:2025

displaystring = strcat(num2str(year),' started');
disp(displaystring);
LimitMatrix = convA(:,[2 4 5]);    %NEMS ID, from, to  --- limit columns loaded later
matrixcol = 4;   % keep track of next column to add to.
```

```
directoryheader = 'U:\aux_iter3_010505\';
%%%% Open outputfile
outputfilename = strcat(directoryheader,'PWlimits_',num2str(year));
fout = fopen(outputfilename,'w');
header = strcat(['ID' char(9) 'from' char(9) 'to']);
%header = 'ID\tfrom\tto';
%fprintf(fout,'ID\tfrom\tto');

for group = 1:12
for segment = 1:3
%for group = 1:1
%for segment = 1:1


%1.  Auxiliary files
if group<10
   GSstring = strcat('g0',num2str(group),'s',num2str(segment));
   auxfile = strcat(directoryheader,'g0',num2str(group),'s',num2str(segment),'_',num2str(year),'.aux');
else
   GSstring = strcat('g',num2str(group),'s',num2str(segment));
   auxfile = strcat(directoryheader,'g',num2str(group),'s',num2str(segment),'_',num2str(year),'.aux');
end
disp(GSstring);
header = strcat([header char(9) '  ' GSstring]);
%fprintf(fout,'\t  %s',GSstring);



%% Call PowerWorld
% process auxliarly file
output = A.ProcessAuxFile(auxfile);
if~(strcmp(output{1},''))
   disp(output{1})
end
clear global output;

%% call PowerWorld
output = A.RunScriptCommand('EnterMode(RUN)');
if~(strcmp(output{1},''))
   disp(output{1})
end
clear global output;
output = A.RunScriptCommand('SolvePrimalLP');
if~(strcmp(output{1},''))
   disp(output{1})
end
%FL = A.GetFieldList('interface');
clear global output;
fieldlist={'IntNum' 'FGName' 'FGLimA' 'FGMW' 'FGPercent'};
%output = A.SendToExcel('interface','',fieldlist);
output = A.GetParametersMultipleElement('interface',fieldlist,'');
if~(strcmp(output{1},''))
   disp(output{1})
   return
```

```
else
   %put into matrix
   paramlist = transpose(output(2));
   IntNum = round(str2num(cell2mat(paramlist{1}{1})));
   FGMW = str2num(cell2mat(paramlist{1}{4}));
%    FGPercent = str2num(cell2mat(paramlist{1}{5}));
   FGLimA = str2num(cell2mat(paramlist{1}{3}));
end
clear global output;

for k = 1:numberofconstraints
   PWID = IntNum(k);
   NEMSID = find(convA(:,1)==PWID);
   flow = FGMW(k);
   flowlimit = FGLimA(k);
   if flow <0
      newflowlimit = 0;
   elseif flowlimit>0
      newflowlimit = min(flowlimit,flow);
   else
      % PowerWorld thinks the flow limit is unlimited.
      newflowlimit = flow;
   end
   LimitMatrix(NEMSID,matrixcol) = newflowlimit;
end
matrixcol = matrixcol+1;


clear paramlist IntNum FGMW FGPercent FGLimA
end %segment
end %group

%% write data to outputfile
fprintf(fout,'%s\n',header);
[rows,cols] = size(LimitMatrix);
for i=1:rows
   fprintf(fout,'%d\t%d\t%d',LimitMatrix(i,1),LimitMatrix(i,2),LimitMatrix(i,3));
   for j=4:cols
      fprintf(fout,'\t%7.3f',LimitMatrix(i,j));
   end
   fprintf(fout,'\n');
end

fclose(fout);
displaystring = strcat(num2str(year),' completed');
disp(displaystring);

clear LimitMatrix;
end %year

% close PowerWorld case

output = A.CloseCase;
disp('Close case')
```

```
%% end PowerWorld SimAuto

delete(A);
```

Sample Auxiliary file

This file is abridged to remove thousands of lines of costs data for each group.

```
DATA (LOAD, [BusNum,LoadID,LoadMW])
{
// BUS  LoadID    Demand
     1    "1 "     56.60
     2    "1 "     23.59
     3    "1 "     24.77
     4    "1 "     22.61
     5    "1 "     13.98
     6    "1 "     14.84
     7    "1 "     13.28
     8    "1 "     15.30
     9    "1 "     81.18
    10    "1 "     16.64
    11    "1 "     21.01
    12    "1 "     19.25
    13    "1 "     19.77
}

DATA (GEN, [BusNum,GenID,GenMWMin,GenMWMax,GenCostModel])
{
// BUS GenID   Min         Max   CostFormat
     1   "1"  0.00     96.1284  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      4.2565      0.5985
    . . .
     95.9682    125.1213
     96.0743    168.7869
     96.0995    168.7869
   </SUBDATA>
// BUS GenID   Min         Max   CostFormat
     2   "1"  0.00     62.5574  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      1.3149      0.5985
     . . .
     62.5553     56.5200
     62.5557     59.1693
     62.5559     60.8000
   </SUBDATA>
// BUS GenID   Min         Max   CostFormat
     3   "1"  0.00     55.1517  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
```

```
      0.0000      0.0000
      2.5177      0.5985
       . . .
     54.9221     71.3175
     55.0229     71.3175
     55.1459     91.3776
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
     4   "1"  0.00     50.3143  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      3.2053      0.5985
       . . .
     50.3035     92.5894
     50.3104     93.9571
     50.3114    107.9450
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
     5   "1"  0.00     24.9739  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      0.4540      0.5985
       . . .
     24.9700     94.8169
     24.9716     94.8169
     24.9731     98.2217
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
     6   "1"  0.00     19.6729  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      5.7813      0.5985
       . . .
     19.6019     82.0980
     19.6191     85.1047
     19.6204     92.3770
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
     7   "1"  0.00     22.9534  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      1.7115      0.5985
       . . .
     22.8319     93.7422
     22.8367     96.6599
     22.9532    101.5360
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
     8   "1"  0.00     43.3131  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      0.6289      0.5985
```

```
      . . .
     43.3067     78.7465
     43.3067     83.1506
     43.3131     95.6777
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
     9   "1"  0.00    153.6210  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      2.7866      0.5985
      . . .
    153.5919     84.1530
    153.6053     84.8801
    153.6091     95.0555
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
    10   "1"  0.00     48.0211  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      0.9839      0.5985
      . . .
     48.0141     94.8169
     48.0153     94.8169
     48.0182     97.4789
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
    11   "1"  0.00     24.0941  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      8.3040      0.5985
      . . .
     24.0702     76.0240
     24.0894     97.8068
     24.0912     97.8068
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
    12   "1"  0.00     36.6682  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      2.4437      0.5985
      . . .
     36.6452     81.6640
     36.6625     97.8068
     36.6669    115.1008
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
    13   "1"  0.00     41.8811  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      0.0000
      6.6375      0.5985
      . . .
     41.8372     60.9539
```

```
     41.8379     68.3500
     41.8523     85.3881
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
    17   "1"  0.00      1.3490  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.5050     35.4108
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
    18   "1"  0.00      1.2300  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000      7.0822
      0.1030     14.1643
      1.2300     28.3286
      1.2300     35.4108
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
    19   "1"  0.00      5.0000  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0000     14.1643
// BUS GenID   Min         Max  CostFormat
    20   "1"  0.00      0.5880  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.0420     35.4108
   </SUBDATA>
// BUS GenID   Min         Max  CostFormat
    21   "1"  0.00      0.7000  "Piecewise Linear"
   <SUBDATA BidCurve>
    //    GW       Price[$/MWhr]
      0.2390     35.4108
   </SUBDATA>
}

DATA (INTERFACE, [IntNum,FGName,FGLimA])
{
       1    ECARtoMAAC    3.368
       2    ECARtoMAIN    3.896
      22    ECARtoSTV     5.398
       3    ECARtoONTcan  1.700
      23    ERCOTtoSPP    0.661
      24    MAACtoECAR    4.000
       5    MAACtoNY      3.312
       6    MAACtoSTV     4.000
       7    MAINtoECAR    3.880
       8    MAINtoMAPP    1.995
      10    MAINtoSTV     6.000
       9    MAINtoSPP     1.900
      25    MAPPtoMAIN    2.023
      26    MAPPtoSTV     2.000
      27    MAPPtoSPP     1.400
      28    MAPPtoNWP     0.102
      29    MAPPtoRA      0.310
      30    MAPPtoMANcan  0.460
```

```
       11    MAPPtoONTcan  0.100
       14    NYtoMAAC      3.956
       31    NYtoNE        1.498
       15    NYtoONTcan    2.027
       16    NYtoQUEcan    1.100
       32    NetoNY        1.475
       13    NEtoQUEcan    1.850
       12    NEtoMARcan    0.300
        4    FRCCtoSTV     2.700
       33    STVtoECAR     6.674
       20    STVtoMAAC     3.750
       21    STVtoMAIN     5.577
       34    STVtoMAPP     1.800
       19    STVtoFRCC     4.594
       35    STVtoSPP      0.650
       36    SPPtoERCOT    0.660
       37    SPPtoMAIN     1.673
       18    SPPtoMAPP     1.512
       38    SPPtoSTV      1.091
       39    SPPtoRA       0.626
       40    NWPtoMAPP     0.150
       41    NWPtoRA       0.766
       42    NWPtoCA       7.951
       43    NWPtoBCcan    2.098
       44    RAtoMAPP      0.308
       45    RAtoSPP       0.420
       46    RAtoNWP       0.000
       47    RAtoCA        3.677
       48    CAtoNWP       6.904
       49    CAtoRA        1.171
       50    CAtoMEX       0.408
       51    BCcantoNWP    2.883
       52    MANcantoMAPP  0.770
       17    ONTcantoECAR  1.700
       53    ONTcantoMAPP  0.150
       54    ONTcantoNY    2.245
       55    QUEcantoNY    1.400
       56    QUEcantoNE    1.481
       57    MARcantoNE    0.700
       58    MEXtoCA       0.408
}
```