



Low Emissions Analysis Platform

Training Exercise: Optimization with LEAP and NEMO

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These exercises are for use with LEAP2020 for Windows and NEMO 1.6.
Download the latest version of LEAP from <https://leap.sei.org/download> before using these exercises.



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1 Least-Cost Electric Generation

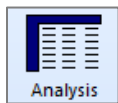
In this simple exercise you will use LEAP’s optimization features with NEMO to investigate a range of different technologies for generating electricity. You will compare the costs of generating electricity including the capital, operating and maintenance and fuel costs of those technologies, and you will perform sensitivity analyses to examine which options are the cheapest when the externality costs of local air pollution are either included or excluded. You will then go on to explore the implications of a cap on CO₂ emissions – how it alters the set of technologies chosen and how it affects the overall cost of the scenario.

This exercise will also show you how to import a year’s worth of hourly electrical load data into LEAP, as a way of describing how demands vary among seasons and times of the day. Finally, the exercise will introduce energy storage modeling and optional constraints for limiting the capacity of certain technologies in optimization.

*Please note that this exercise is a highly simplified representation of an electric generating system and the data values provided are not intended to be realistic. **Please do not cite or use the data shown in this exercise in any real study.***

 **NB: this exercise requires Microsoft Excel as well as LEAP and NEMO.**

1.1 Entering Electric Generation Data

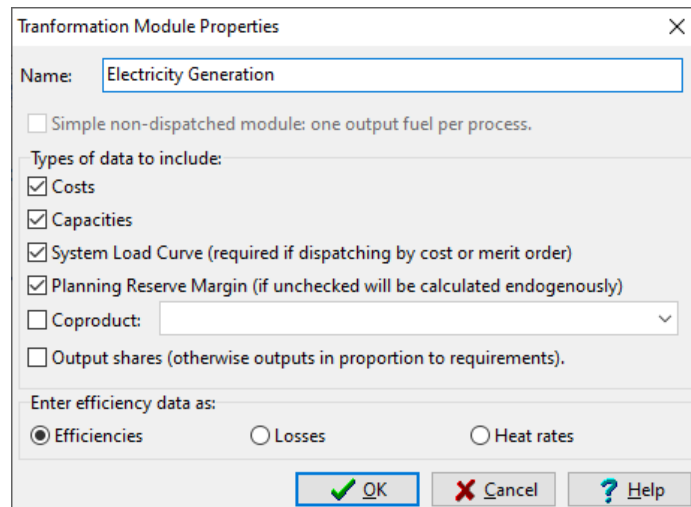


Start by opening the LEAP area “Optimization Exercise” by clicking Area: Open, and then click Area: Revert to Version and select “Optimization Exercise Start”. This data set is partially completed already. We recommend you immediately save this area with a new name such as “Optimization Exercise [your name]”.

Under the Demand branches, a single branch specifies that the demand from electricity grows from nothing in the base year (2010) to 200 Thousand GWh in the end year (2020). This information is entered in the **Total Energy** variable of a single *Technology with Total Energy* (⚙️) branch in the Current Accounts scenario. In this simple exercise the same energy demand assumptions will be used in all scenarios.

Now look at the Transformation tree branches. You will see a single module describing transmission and distribution losses. Here we have created a simple Transformation module containing an assumption of 10% electrical losses. This value is assumed to stay the same in all years and across all scenarios.

Your first data entry task is to create a new module that will be used to



Transformation Module Properties

Name: Electricity Generation

Simple non-dispatched module: one output fuel per process.

Types of data to include:

- Costs
- Capacities
- System Load Curve (required if dispatching by cost or merit order)
- Planning Reserve Margin (if unchecked will be calculated endogenously)
- Coproduct: [dropdown]
- Output shares (otherwise outputs in proportion to requirements).

Enter efficiency data as:

Efficiencies Losses Heat rates

OK Cancel Help

describe the various possible electric generation technologies.

Start by adding a new Transformation module called “Electricity Generation” and set its properties to include costs, capacities, a system load curve and a planning reserve margin. Efficiency data should be set to be entered directly (as percentage efficiency values). Make sure the new module appears below the “Transmission and Distribution” module in the tree’s branch structure.

Once you have created the module, you can start to enter the basic data describing its various technologies. Enter all the following data for the Current Accounts scenario. Set the planning reserve margin to 25% and make sure the module has electricity as a single output fuel.

Set the **Shortfall Rule** for electricity to *RequirementsRemainUnmet* (this is required for optimization), and leave the other default properties for the output fuel unchanged. No data should be entered for import and export targets.

Next you can specify the set of electric generation technologies to be evaluated. Create each one as a separate process within the Electricity Generation module and do this while editing the Current Accounts scenario. The following table provides the data you will need to define these processes.

Process	Feedstock	Efficiency (%)	Max Availability (%)	Capacity Credit (%)	Capital Cost (Thousand \$/MW)	Fixed O&M (Thousand \$/MW)	Variable O&M (\$/MWh)	Fuel Costs	Lifetime (yrs)
NGCC	Natural Gas	45	85	100	1900	10	3	\$7/MMBTU	30
Wind	Wind	100	47	20	2300	20	4	n/a	25
Coal	Coal Bituminous	35	90	100	2200	40	3	\$100/Tonne	30
Hydro	Hydro	100	60	50	9000	30	5	n/a	40

Most of the above data in this table needs to be entered for the various variables defined for each process. Feedstock fuel costs need to be specified within the Resources branches of the tree. Enter the natural gas and coal fuel costs at both the **Indigenous Cost** and **Import Cost** variables (under the Resources\Primary branches). Ensure that these cost variables are correctly referenced in the **Fuel Cost** variable for each power plant feedstock fuel.

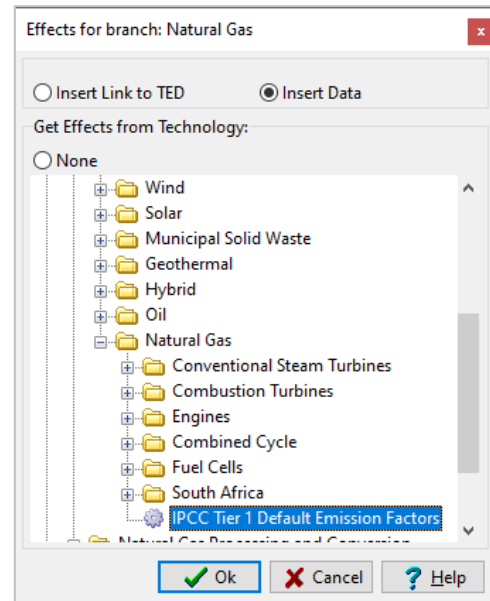
To ensure the energy balances are correctly calculated, make sure that you specify very large reserves of natural gas and coal bituminous and very large availability of wind and hydro power. In Current Accounts, enter *Unlimited* GJ as the **Base Year Reserves** for these fuels under the Resources\Primary branches. Enter the same value for wind and hydro availability in the **Yield** variable.

In addition to the data in the above table, ensure that the **Interest Rate** variable is equal to the model’s discount rate of 5%. Make sure the **Exogenous Capacity** variables are all set to zero. Finally, set the **Dispatch Rule** to *RunningCost*.

In this simple exercise we are not trying to represent actual historical patterns of dispatch, and thus we will not be using the **Historical Production** variable to tell LEAP how much of each process to dispatch. Instead we will be using LEAP’s optimization calculations to calculate process capacity values consistent with minimizing costs while meeting demands. Setting the **First Simulation Year** to a date equal to or before the base year of the study tells LEAP to

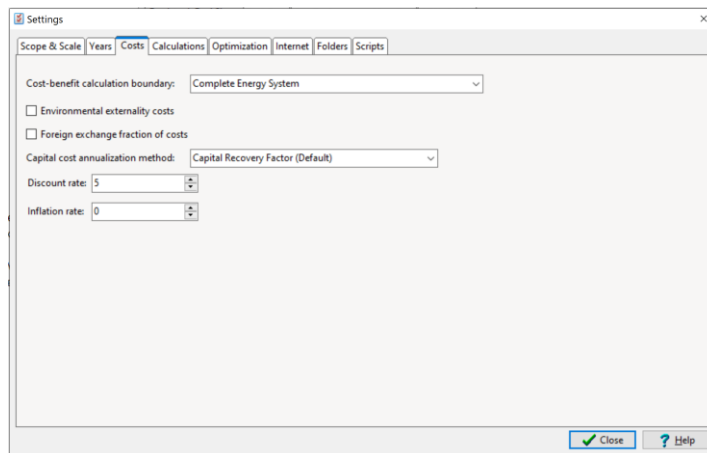
ignore the **Historical Production** variable. To accomplish this, you may enter the expression *BaseYear* into the **First Simulation Year** for all processes.

Before leaving the processes branches, make sure you have specified a set of emission factors for each process. Using the techniques you first followed in Exercise 1.5., add IPCC Tier 1 emission factors for the coal and NGCC (natural gas) power plants. Right-click each relevant feedstock fuel branch (those marked with the 🟡 icon), and then select the *Add multiple effects* option (🌱). This will display the box shown on the right. Select the appropriate emission factors stored in the TED database.



Finally, visit the Costs tab of **Settings** (shown below). Here you will need to set a few options that will be used to calculate cost results. Make sure this screen has the following settings:

- The *Cost-benefit calculation boundary* should be set to “Complete Energy System”.
- *Environmental externality costs* can initially be switched off. Also, foreign exchange costs are not used in this exercise, so that can also be left off.
- Set the *Discount rate* to 5%
- The *Capital cost annualization method* should be set to “Capital Recovery Factor (Default)”. This method is required when using optimization.




1.2 Creating Load Shapes by Importing Hourly Load Data


Next you will create a set of data that describe how the electric generation load varies among different seasons and times of day. The variations in the electric load are important in determining what mix of base load or peak load plants should be built and operated.

Creating and using this load shape in LEAP is a four-step process.


1. **Time Slices:** First you will specify a set of time slices into which each year will be divided. In this example we will divide each year into four seasons and each day will be divided into 24 hours.

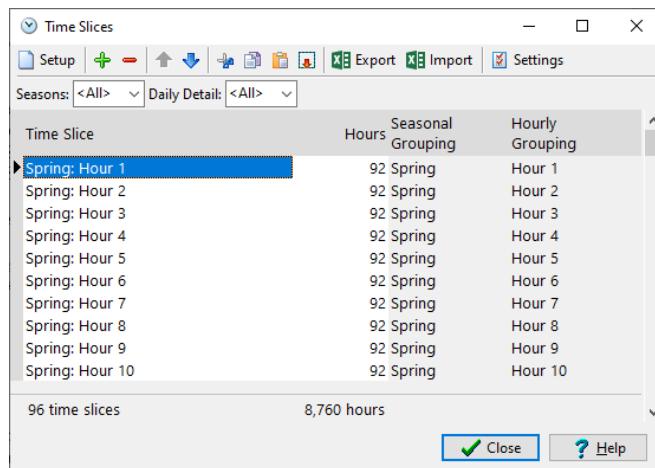
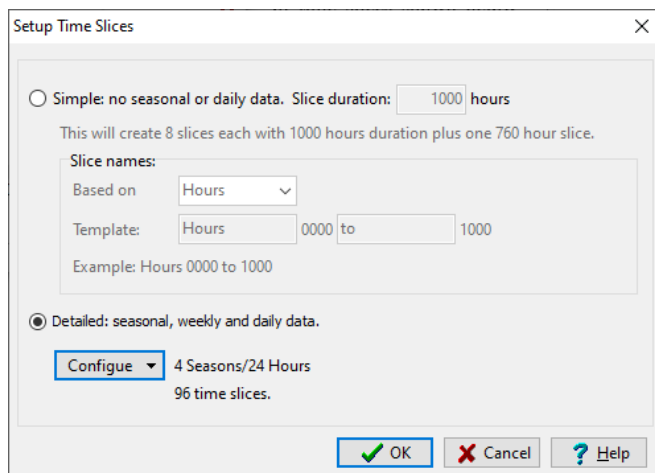
2.  **Hourly Data Spreadsheet:** Second, you will select a set of predefined hourly data that describes how the electric load varied across all 8760 hours of a single year. This hourly data is predefined and stored in a separate Microsoft Excel spreadsheet provided to you.
3. **Yearly Shape:** Third, you will use LEAP's **Yearly Shapes** screen to import the hourly data contained in the spreadsheet and automatically map it to the time slices you have created.
4. **System Energy Load Shape:** Finally, you will use this newly created load shape in your LEAP data set by assigning it to the **System Energy Load Shape** variable in your analysis.

Let's follow each of those steps in detail.

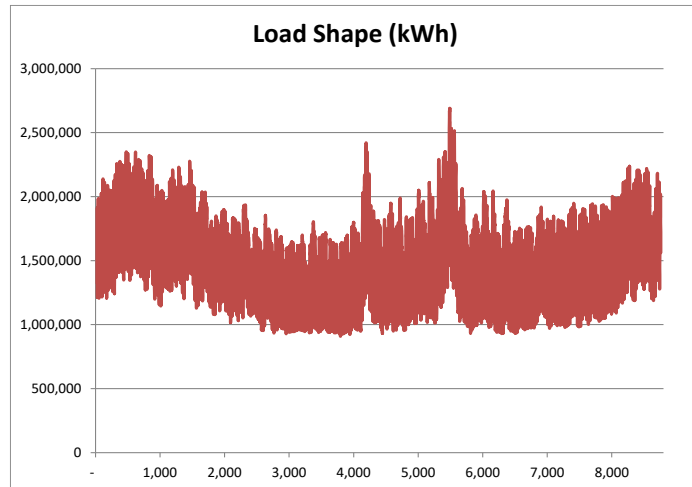
1. **Time Slices:** First let's create a detailed set of time slices. Go to the General: Time Slices screen and click the Setup toolbar button (). Choose **Detailed** and then set up slices to include four seasons and 24 hourly slices. In this exercise we will not use any weekday/weekend slicing.

Once you click OK, LEAP will generate the detailed set of time slices shown to the right. Each slice will include data describing its number of hours. You can now return to the main screen.

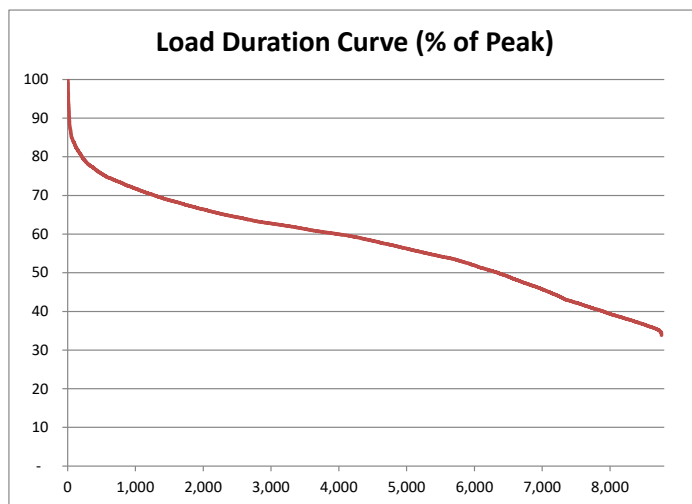
2.  **Hourly Spreadsheet Data:** Next, open up a copy of Microsoft Excel and load the spreadsheet **Yearly Shape Data.xlsx**.




Notice that this spreadsheet contains hourly data for all 8760 hours of a single year, from the first hour of January 1st to the last hour of December 31st. The numbered hours are listed in the “Hour” column (column A) from 1 to 8760 while the corresponding electric demands are listed in the “kWh” column (column B). These values are plotted in the “Load Shape” chart in the spreadsheet (shown here). Notice the large variations both among seasons and between different times of the day and days of the week.



In columns C, D and E these same data have been reorganized by sorting the values from high to low and normalizing them in percentage terms against the annual peak value to produce a standard load duration curve that shows how demand varies from the hour with the highest demand to the hour with the lowest. This



load duration curve is also shown here. Notice that as a result of the sorting operation, the load duration curve loses any information about seasons, days of the week or times of the day.

- Yearly Shape:** You will now import this hourly data into LEAP. Keeping Excel open, go to the General: **Yearly Shapes** screen and select the toolbar option  *Import from Annual Shape (e.g. Hourly)*. A dialog box will appear as shown here. Set this up to import values as an “Energy Load Shape (% of annual load)”, since this type of load shape is required when using optimization in LEAP.

✕

Import annual hourly load data into yearly shape

Import values as: Energy Load Shape (% of annual load) ▾

New yearly profile name: SystemShape

Excel range: kWh ▾

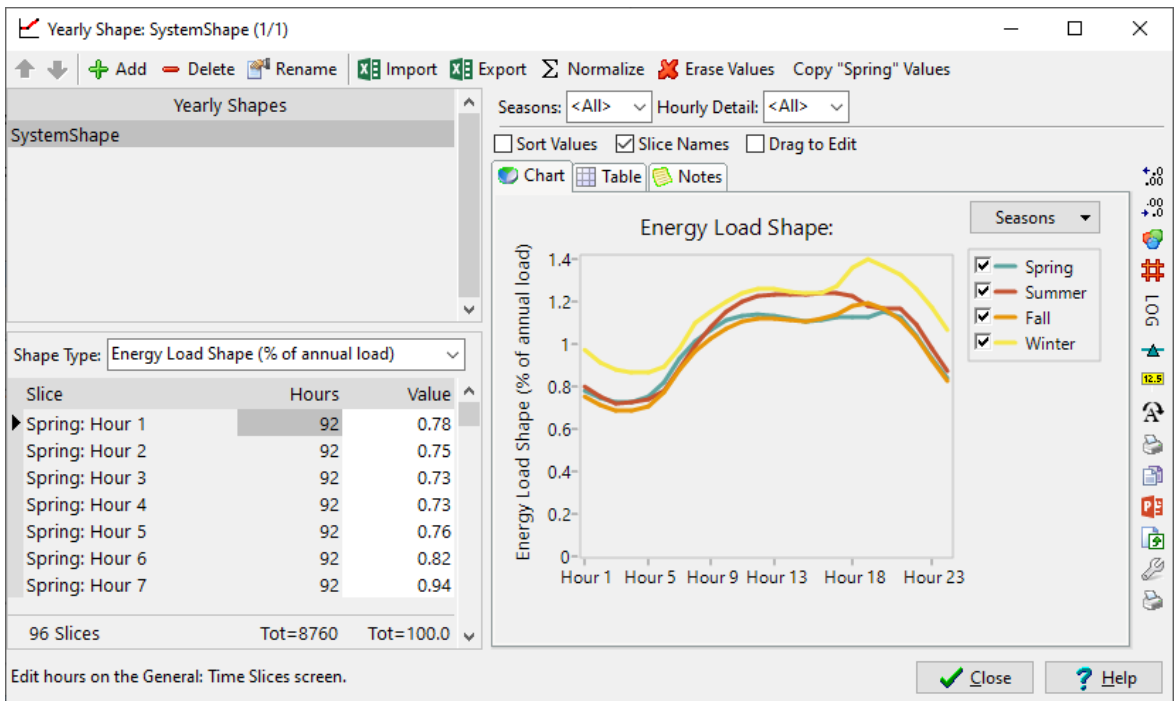
Hour of first hour in first Monday in shape year: 1 ▾

Create a new load shape by importing one year of hourly loads.
Loads must be in chronological order (1 x 8760 or 365 x 24 hours).

✔ OK
✘ Cancel

Choose the Excel range named “kWh” as the import range: this range contains the kWh values in column B of the spreadsheet. Finally, remember to enter a name for the new yearly shape. We suggest you name it “SystemShape”.

When you click OK, LEAP will import all of the hourly values in the spreadsheet and automatically map these values to the time slices you specified in step 1 above. The result will be a yearly shape that should look like the one shown below.




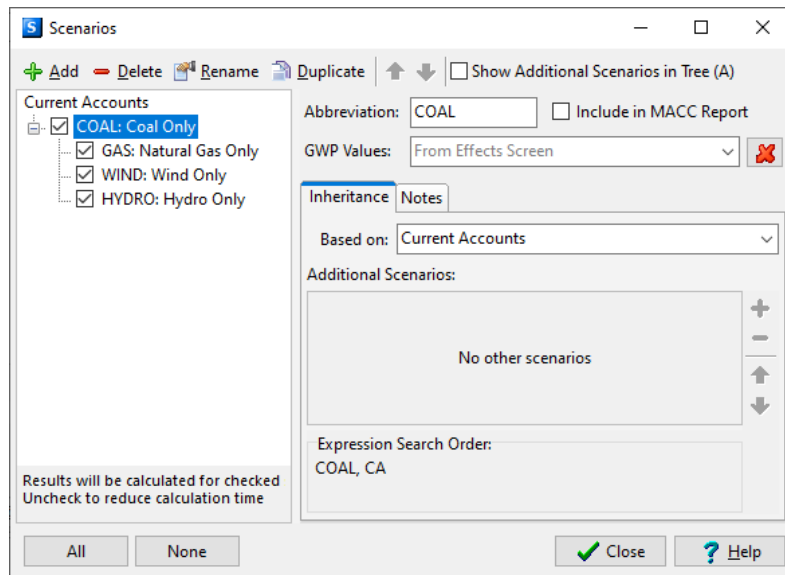
4. **System Energy Load Shape:** The final step in using this data requires that you assign this newly created load shape to the **System Energy Load Shape** variable. Exit the **Yearly Shapes** screen and then in **Analysis View** locate the Transformation\Electricity Generation branch. In Current Accounts, enter the following expression for the **System Energy Load Shape** variable:

YearlyShape(SystemShape)


1.3 Simulation Scenarios to Explore Technology Characteristics

You are now ready to explore the costs and emissions associated with different technologies. Before exploring a least-cost scenario using LEAP's optimization features, let's first set up some very simple scenarios, each of which looks at just a single generation technology.

Go to the **Scenarios** screen () and create a first scenario named "Coal Only" that inherits from your Current Accounts data. Next create



three more scenarios each of which directly inherits from the Coal scenario. Name these: "Natural Gas Only", "Wind Only", and "Hydro Only". Once these have been created, the **Scenarios** screen will look like the screen shown above. NB: to minimize data entry it is important that the three additional scenarios inherit directly from the Coal Only scenario.

Once you have created these four scenarios, return to the main screen and then select the **Endogenous Capacity** variable for the Coal Only scenario. Use the **Add** button () on the right of this screen to add the Coal process to this list and enter the value of 100 MW for the *Addition Size Expression* for this variable.

Doing this tells LEAP that in this scenario LEAP should automatically add coal capacity whenever it is needed. In LEAP's standard **simulation** calculations, it is up to you to tell LEAP *what* types of power plants to add, although LEAP will decide *when* to add them. Later on, when we come to use LEAP's optimization calculations, you will see that LEAP and NEMO will decide both of these questions: *what* processes to add and *when* to add them.

Repeat this same process for the three other scenarios: Natural Gas Only, Wind Only, and Hydro Only. In each case, add only the one process relevant for that scenario (deleting the coal process), and use 100 MW as the *Addition Size Expression*.

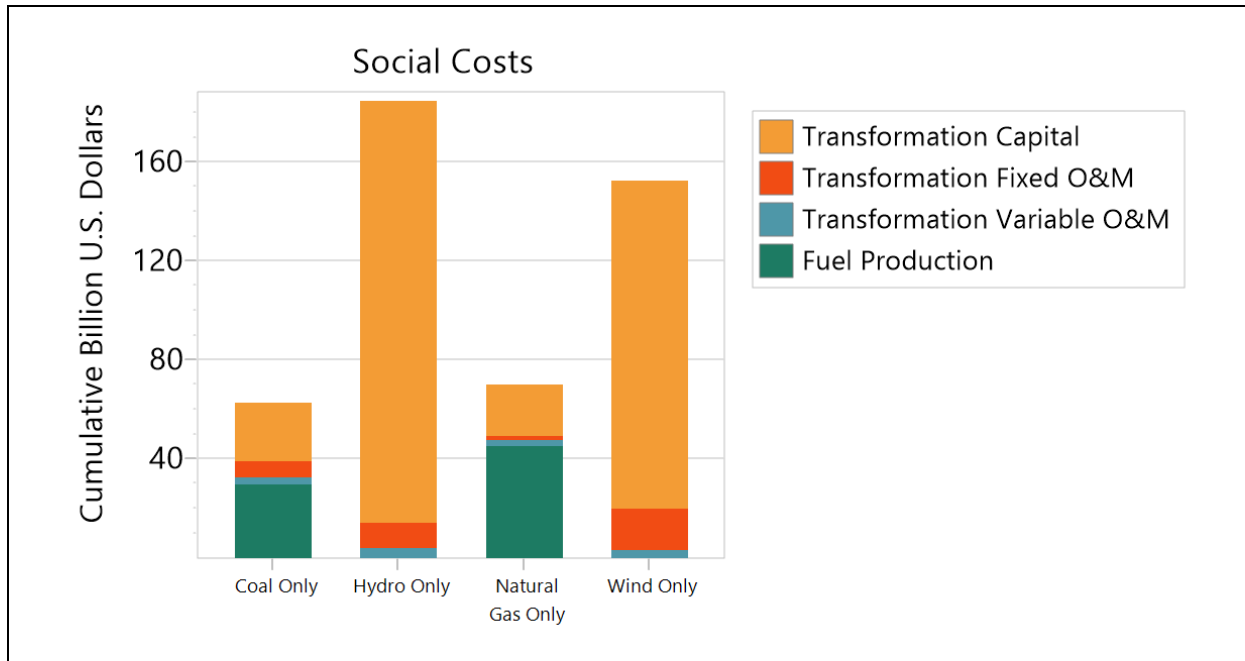
1.3.1 Results

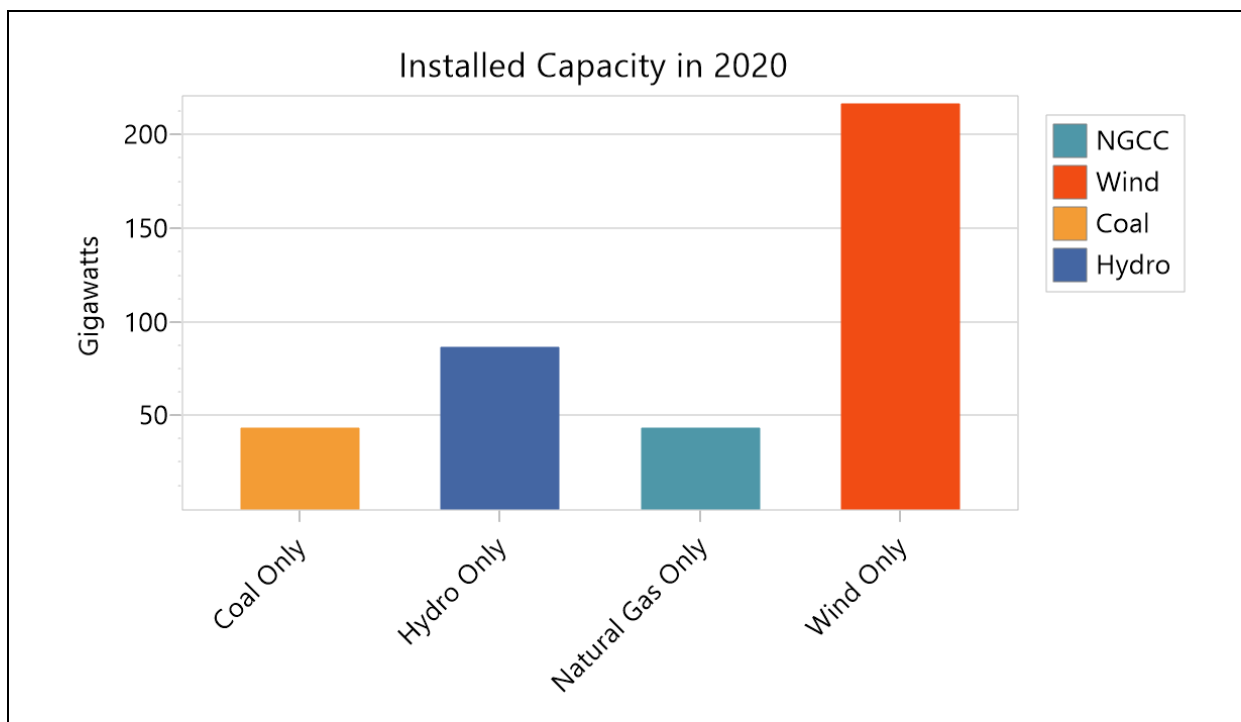


You are now ready to see some results for these scenarios. Go to the **Results View** and create two different charts as follows:

1. **Social Costs:** First create a chart comparing the total cumulative, discounted social costs in 2020 (at the top area branch) for each scenario. Make sure you configure the chart to show *All Scenarios* on the X-axis and *All Cost Categories* in the legend. Save this chart as a favorite chart called “Costs by Scenario”.
2. **Capacity:** Next create a chart showing total installed capacity in 2020 in each scenario. Save this chart as a favorite chart called “Capacity by Scenario”.

These two charts should look like those shown below:

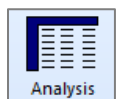




Use LEAP to analyze the results and try to answer the following questions:

1. Why is coal the cheapest option?
2. Why does LEAP incorporate more capacity for the Wind Only and Hydro Only scenarios if the electricity demand is the same in all scenarios?

1.4 Incorporating Externality Values



The results you obtained above are influenced by the fact that we have so far ignored a crucial factor: the damage costs associated with pollution created by burning fossil fuels. These costs are often ignored because they are not directly monetized in most energy systems. However, they are a real cost and cause real economic impacts such as damage to human health and crops.

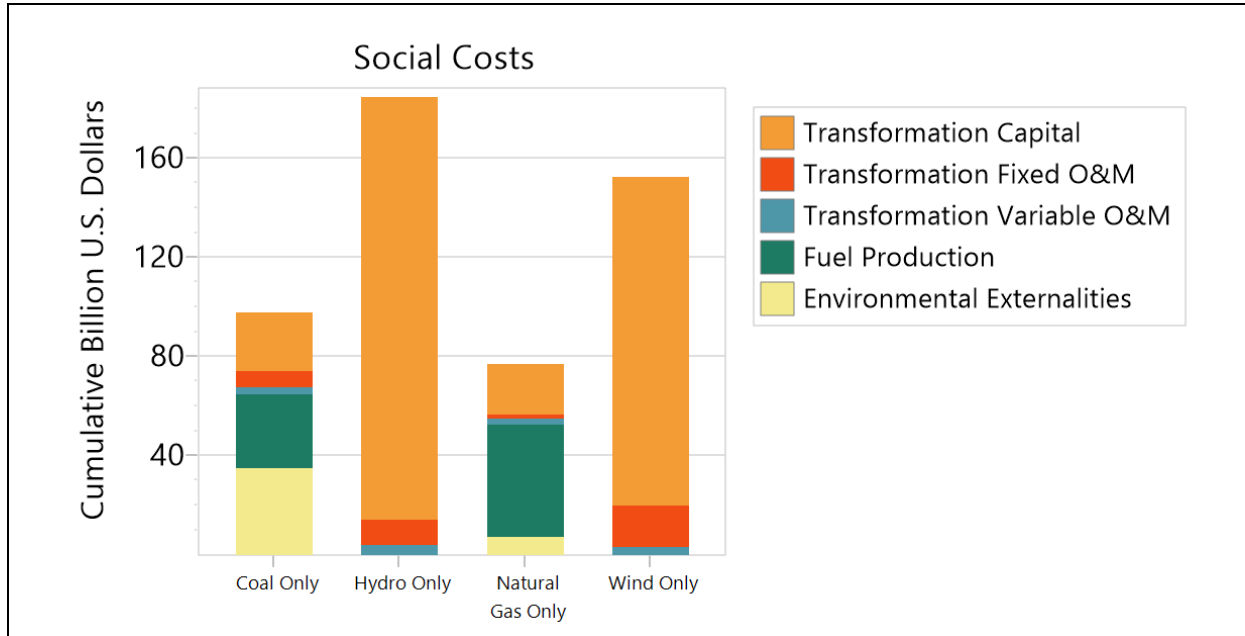
Next you will enter data that describes these externality values. Go back to the **Costing** tab on the **Settings** screen and make sure that **Environmental Externality Costs** is checked on. Now return to the **Analysis View** and under the top level “Effects” branch in the tree, add two new branches for the effects nitrogen oxides (NO_x) and sulfur dioxide (SO₂).

Externality	
Pollutant	Value (\$/kg)
NOx	7
SO2	2

Now in the **Externality Cost** variable, enter the local air pollution (i.e. non-climate related) externality values given in the table above in \$/kg. Enter this data for the Current Accounts scenario so that these externality values are used by all the scenarios. We will deal with climate-related damage costs a bit later on.



Now select the **Results View** again. Once LEAP has recalculated its results, show the favorite result **Costs by Scenario**. You should see a chart like the one below. Notice that LEAP has now calculated a new set of costs corresponding to externality costs.



Use LEAP to analyze the results and try to answer the following questions:

- 1. How did the results change and why?*
- 2. What other important types of externalities have we ignored in these calculations?*

1.5 Installing NEMO

If you haven't already installed NEMO, download the NEMO installer from <https://leap.sei.org/download/> (note: the installer is a large file, so downloading it may take a while). Then quit LEAP, and run the installer to install NEMO and have it integrated with LEAP. Finally, turn LEAP back on, and go to the **Help: About** screen to check that LEAP has properly recognized NEMO.

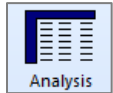
Finally, go to the **General: Settings** screen and open the **Optimization** tab. Check that NEMO is listed as an installed optimization framework and that Cbc is listed as one of the installed solvers. If not, try the **Reset NEMO** option and restart LEAP.

1.6 Using Optimization to Identify a Least-Cost Scenario

You are now ready to try out LEAP's optimization capabilities. These will allow LEAP to automatically decide what combination of power plants will meet demands at the lowest cost.

Before leaving the Optimization tab in the **Settings** screen, check that “Enable Emission Constraints” is switched on.

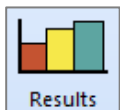
Now set up a new scenario in which you will use optimization. Go to the **Scenarios** screen and create a new scenario called “Optimization” that inherits directly from Current Accounts.



Return to the main screen in analysis view and select the Optimization scenario. You only need to set a simple setting to use optimization since you have already entered all of the basic data needed by the optimization calculations. LEAP will automatically make use of the same data you already entered in your simulation calculations.

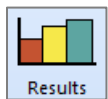
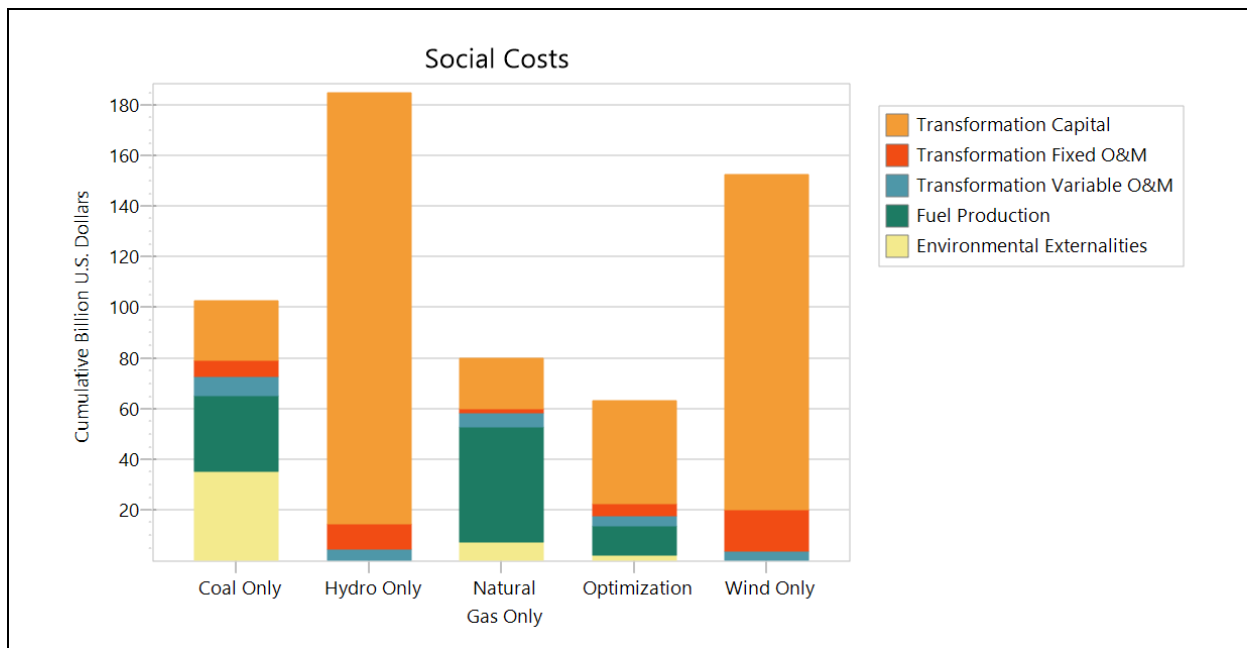
Select the Transformation\Electricity Generation branch and then select the **Optimize** variable. If you do not see this variable, check that you are currently editing the Optimization scenario (this variable does not appear in Current Accounts). Enter *NEMO(Cbc)*, which tells LEAP to optimize the Electricity Generation module using NEMO and the open-source Cbc solver. Alternatively, you can click on the **E** button at the end of the expression box and select from the list of available solvers. Note that NEMO is delivered with two open-source solvers, Cbc and GLPK. Cbc generally offers better performance for LEAP-NEMO models.

Note also that you do not need to set the **Dispatch Rule** for this scenario, since LEAP will use the optimization calculations to decide how much to dispatch each process. Thus, the **Dispatch Rule** is hidden for any scenarios using optimization. That’s all you have to do to use optimization in LEAP!

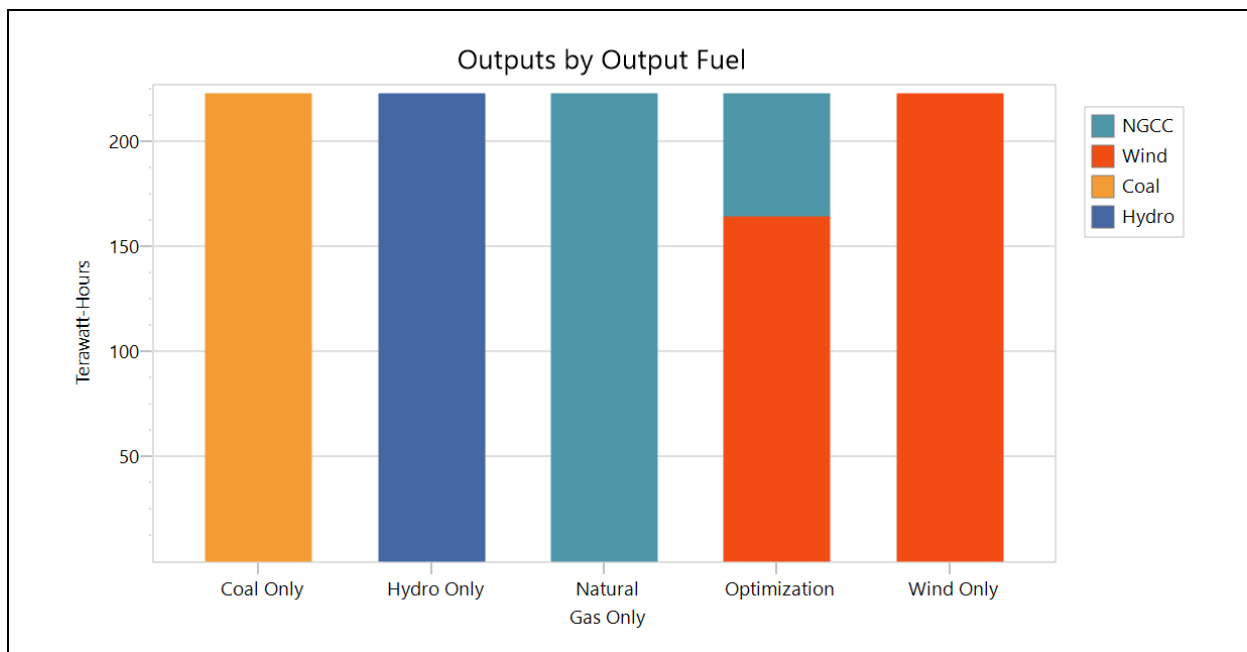


Now select the **Results View** again. LEAP will again recalculate its results. You may notice that during its calculations LEAP will appear to pause. This is due to its calling NEMO to carry out the optimization.

Once calculations are complete, you can again show the favorite result Costs by Scenario. You should see a chart like the one shown below. Notice that LEAP has now created results for the new optimization scenario. You should see that total social costs are slightly cheaper than even the cheapest of the other scenarios you created previously.

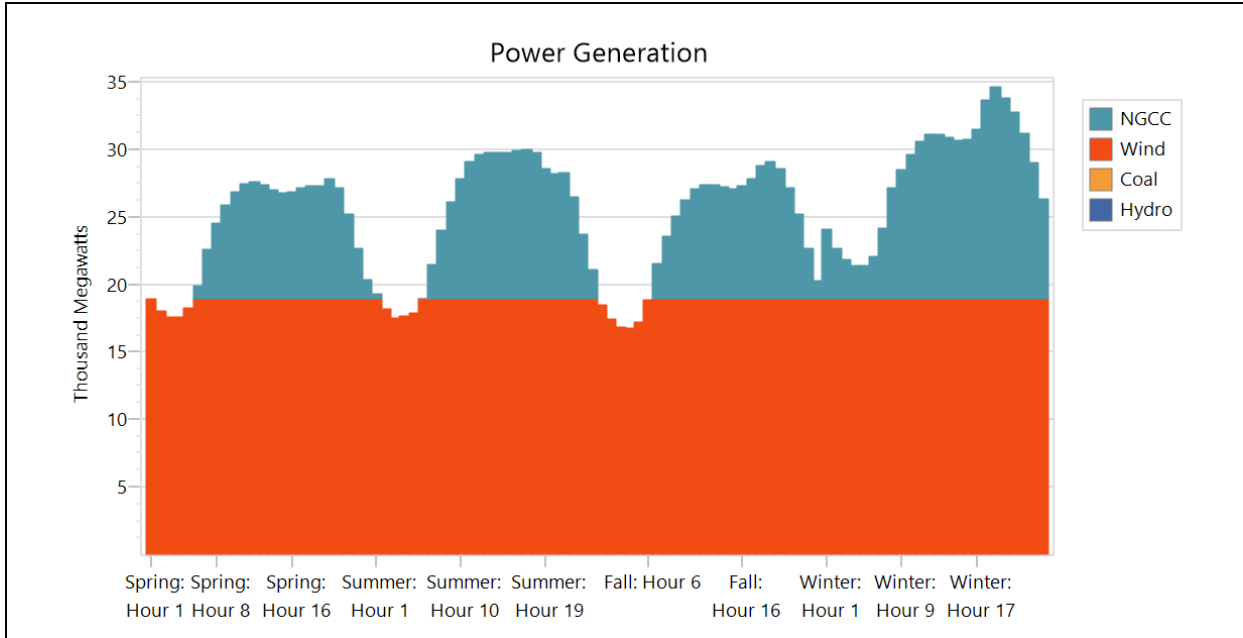


To see how this is possible, let's look at another chart showing **Transformation: Outputs by Output Fuel** by process for each scenario in 2020.



Notice that unlike in the single-technology simulation scenarios, in the Optimization scenario LEAP has chosen a mix of power plants. Since the load shape we entered earlier varies by season and time of day, there will be some periods where a very high peak demand exists. These periods favor power plants that are relatively cheap to build but expensive to operate (NGCC). Base load periods favor power plants that are more capital intensive, but which have low running costs (e.g. wind).

Choose the results report **Transformation: Power Generation** and select the Optimization scenario to see how power was dispatched in each time slice. Make sure you select **All Branches** for the chart legend and **All Time Slices** for the X Axis. You should see a chart like the one below. Notice how the **Wind** is being used as much as possible while the **Natural Gas** plant (with higher fuel and operating costs) is used only to meet the peaks in demand.

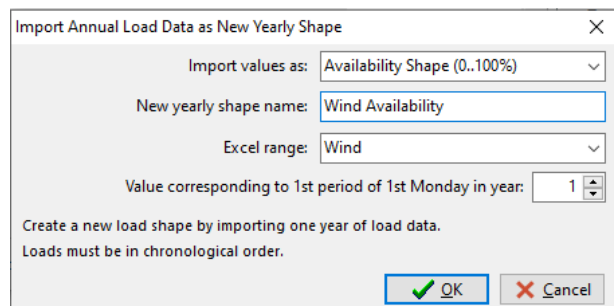


1.7 Making the Model More Realistic

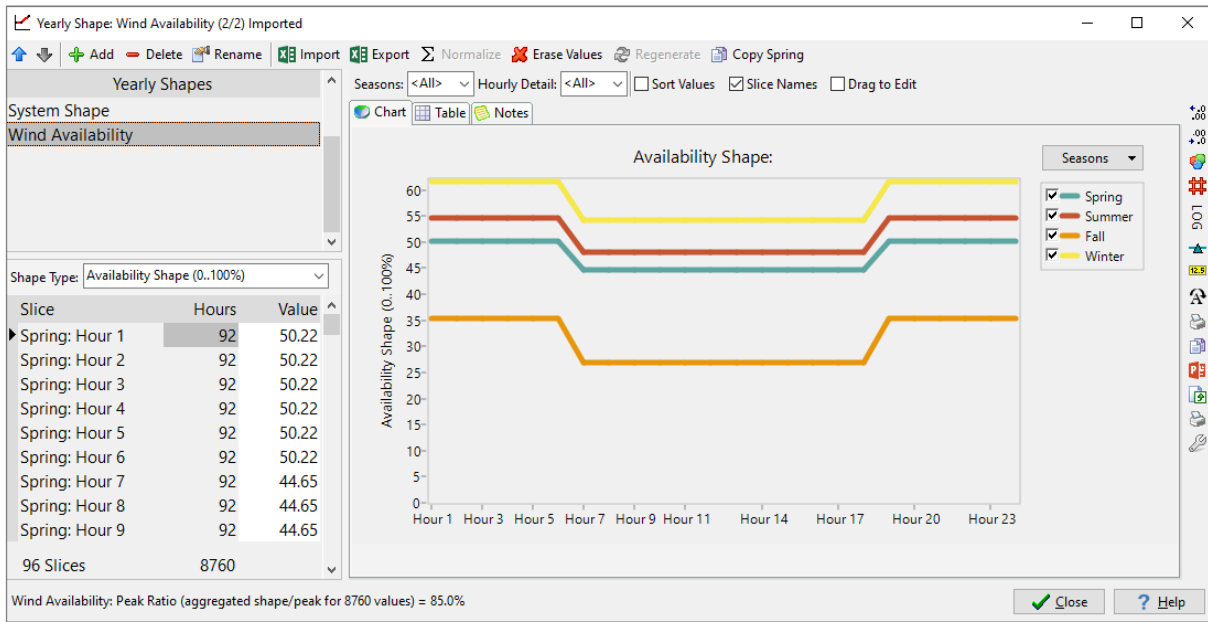
One problem with this result is that we have used a constant **Maximum Availability** for wind (47%). This implies that 47% of installed wind capacity is available to be dispatched in each time slice. In reality, however, the availability of wind will depend both on the season and the time of day. Let's more accurately reflect that and see what effect this has on the above results.

Return to the Analysis View, then create a new scenario that inherits from the optimization scenario. Call it "Better Wind" (BWIND). Next, return to the General: Yearly Shapes screen while ensuring that you have the "**Yearly Shape Data.xlsx**" file (used earlier) open in Excel.

In the Yearly Shapes screen, click the **Import** button and choose **Import from Annual Shape**. Create a new shape called "Wind Availability", which must be marked as an **Availability Shape** using the options in the import dialog box. Import from range named "Wind". The dialog box should look like the one shown here.



Once the shape has been imported, the Yearly Shapes screen should look like this:

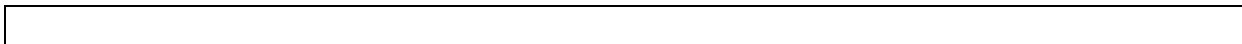


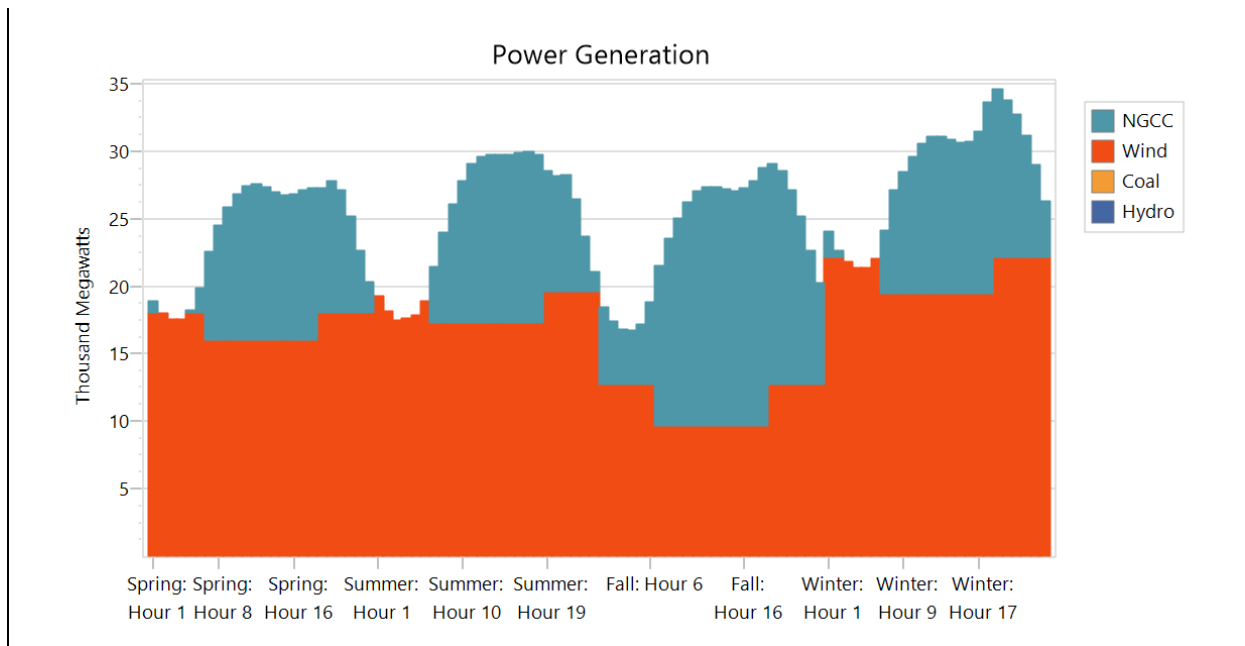
Now return to the Analysis View and select the “Better Wind” scenario. For the Wind process in the Electricity Generation module, specify the more realistic **Maximum Availability** values for wind by replacing the constant 47 value with an expression that links to the yearly shape you just created. The expression should read:

YearlyShape(Wind Availability)

You can either type this, or you can click on the **E** button at the end of the expression box and select from the list of available Yearly Shapes.

Now return to the Results view (which will require some recalculations) and view the Power Generation chart again. The overall result is similar: a mix of wind and natural gas is still the cheapest, although you should now see a more realistic picture of when wind and gas need to be utilized as show below.





1.8 Using Constraints to Specify a CO₂ Cap

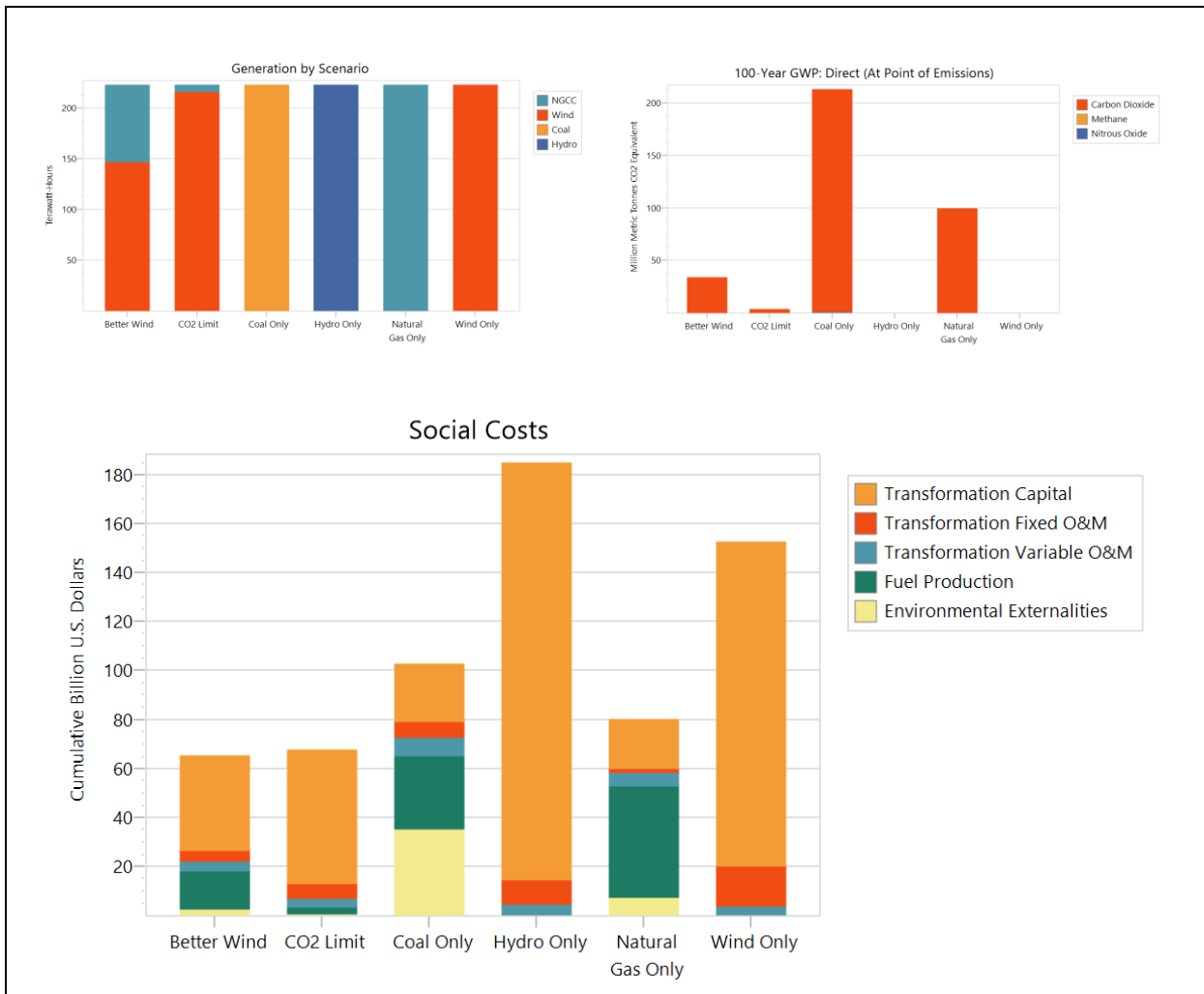
In this next part of the exercise you will create an additional scenario that looks at how the least cost choice of technologies will change if a maximum level of CO₂ emissions is imposed on the system.

To create an emissions constraint, first return to the Optimization tab in the **Settings** screen and make sure that the *Enable Emissions Constraints* box is checked on.

Now return to the main screen and add a new effect under the Effects branch for Carbon Dioxide. For Currents Accounts and all existing scenarios, no constraint is needed so simply leave the default *Unlimited* expression in the **Annual Emission Constraint** variable.

Next, go to the **Scenarios** screen and create a new scenario called “CO₂ Limit” that inherits from the Better Wind scenario. Return to main screen and for this scenario enter a value of 3 Million Metric Tonnes in the **Annual Emission Constraint** variable for Carbon Dioxide.

Finally, select **Results View** again and look at results for electricity generation, total GHG emissions and total social costs. You should see charts like those below.



Use LEAP to analyze the results and try to answer the following questions:

- 1. What effect does the emissions cap have on the optimal installed capacity?*
- 2. How much do overall social costs increase because of the CO₂ emissions cap?*

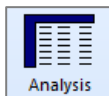
1.9 An Alternative Approach to Modeling CO₂ Damages

Instead of specifying a CO₂ emissions cap, an alternative way to model optimal energy systems that account for climate damages is to use an externality value for CO₂. Try this out yourself by creating another scenario that inherits from “Better Wind” and instead of specifying the annual emission constraint for CO₂, enter different values for the social cost of CO₂.

Through trial and error, try to find out the approximate CO₂ externality value (\$/tonne) that yields the same level of GHG emissions as was achieved by specifying the emissions cap of 3 million MT in section 1.8. We recommend testing in increments of \$50/tonne. Bear in mind though that this simple model assumes that emissions can only be reduced by changing generating options. It does not reflect other likely options such as energy efficiency or T&D loss reduction. Therefore, costs estimates are likely high.

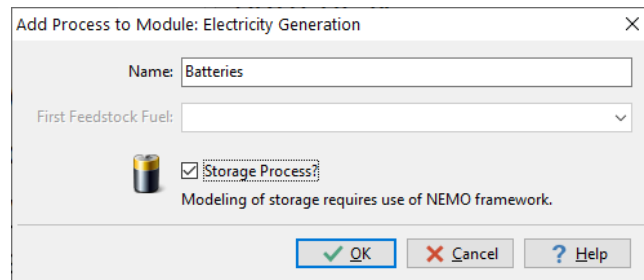
1.10 Modeling Storage and Capacity Constraints

Now you will add a storage process to the model and tell LEAP to include or exclude it in certain scenarios. Note that LEAP can only model storage in scenarios that are optimized with NEMO.



Return to the **Analysis View**, and add a new process to the Electricity Generation module.

Name the process “Batteries”, and check the Storage Process option in the Add Process dialog box.



In the Current Accounts scenario, specify the following properties for Batteries:

- Process Efficiency: 90%
- Maximum Availability: 95%
- Capital Cost: 2,500 thousand dollars/MW
- Fixed OM Cost: 20 thousand dollars/MW
- Variable OM Cost: 1 dollar/MWh
- Capacity Credit: 95%
- Full Load Hours: 8
- Lifetime: 20 years
- Interest Rate: DiscountRate

Leave **Minimum Charge** and **Starting Charge** set to 0, and do not change the default values for the **Storage Carryover** variables.

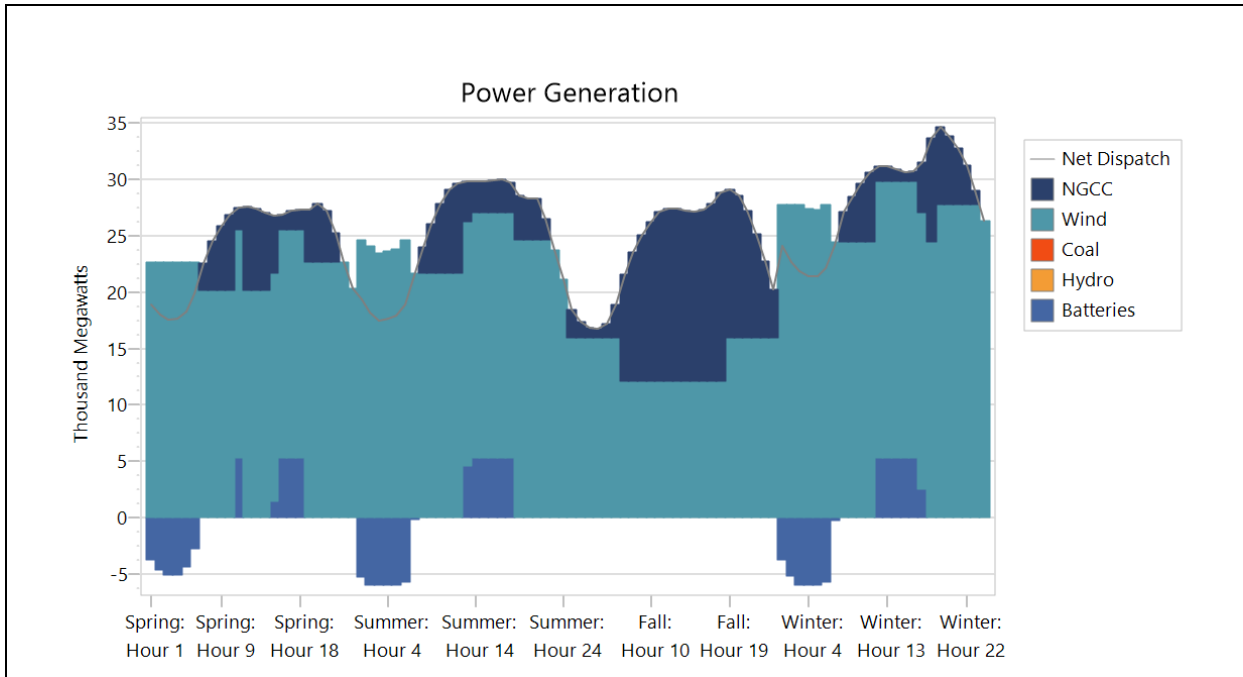
Then switch to the Optimization scenario, and set the **Maximum Capacity** for Batteries to 0 MW. This will prevent Batteries from being built in all of your existing optimized scenarios.

Finally, in the **Scenarios** screen (S), add a new scenario named “Better Wind With Batteries” that inherits from Better Wind. Change to the new scenario in the **Analysis View**, and set the

Maximum Capacity for Batteries to “Unlimited” (enabling Batteries as an option in this scenario).



After entering these data and expressions, open the **Results View**, and look at power generation in the Better Wind With Batteries scenario in 2020. You should see a chart like the following.



Negative generation by Batteries on this chart represents times when the process is charging, and positive generation times when it is discharging. Notice how LEAP has added a “Net Dispatch” line to highlight when surplus generation is being used to charge Batteries.

Compare these results to power generation in the Better Wind scenario. How do the two scenarios differ?

1.11 Using Your Own Data

Now go back and review the capital, O&M and fuel costs used in this exercise, as well as the technical parameters including lifetime, efficiency, maximum availability and capacity credit.

Bear in mind that the values used in this exercise are only sample values: they are not necessarily intended to be realistic (and of course you should not use them in any real study!).

- How do these values compare to the costs of electric generation in your country?
- Try replacing the capital and fuel costs used in this exercise with your own data (if available). How does the optimal mix of power plants change?

- Finally, think about which of these variables are likely to change in the future. For example, you may want to consider how many renewable technologies such as solar and wind energy have been getting significantly cheaper in recent decades, while fossil fuel prices (especially oil) generally have been rising. Try entering some growth expressions to describe these trends. What impact do these changes have on the optimal mix of power plants?