NERA
ECONOMIC CONSULTING

SIMPLIFIED MODEL OF LOCATIONAL MARGINAL PRICING

USER GUIDE

11 SEPTEMBER 2020

Insight in Economics™

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Model Setup | **Installation Guide**

Step 1: Download a Solver and Open the Model

Important note: Our model requires the use of a linear solver to operate with the same user interface and, depending on the choice of solver, minor edits to the virtual basic macros. The underlying model is built in Excel's default solver add-in, and any linear solver that can read Excel's solver may be able to run the model. It is your responsibility to find the solver that best works for you and meets any IT standards that you or your organisation have. Please see our full model qualifications, assumptions, and limiting conditions in this user guide.

1. Download your solver of choice before progressing. We used the latest stable version of OpenSolver (from https://opensolver.org/) to run the model (OpenSolver 2.9.0).[1] We illustrate the model setup using this solver in this user guide to illustrate how one might incorporate a solver into the excel model. The remainder of Step 1 may differ for other solvers.

2. Please ensure Microsoft Excel is closed to begin.

3. Once, you have downloaded your solver, extract the ZIP file and save the contents on your computer all in the same folder – for instance, on your desktop. Be sure to extract the file. You may save/extract the file anywhere, but **do not move the files once you have extracted them.**

4. Open your solver file, in our case "OpenSolver.xlam", from your saved folder – this will open Microsoft Excel

5. Save the model file "Simplified Model.xlsm" on your computer – for instance, on your desktop. You may save the file anywhere, but **do not move the model file once you have saved it.** It may be helpful to save in the same folder as your solver files.

6. Open "Simplified Model.xlsm".

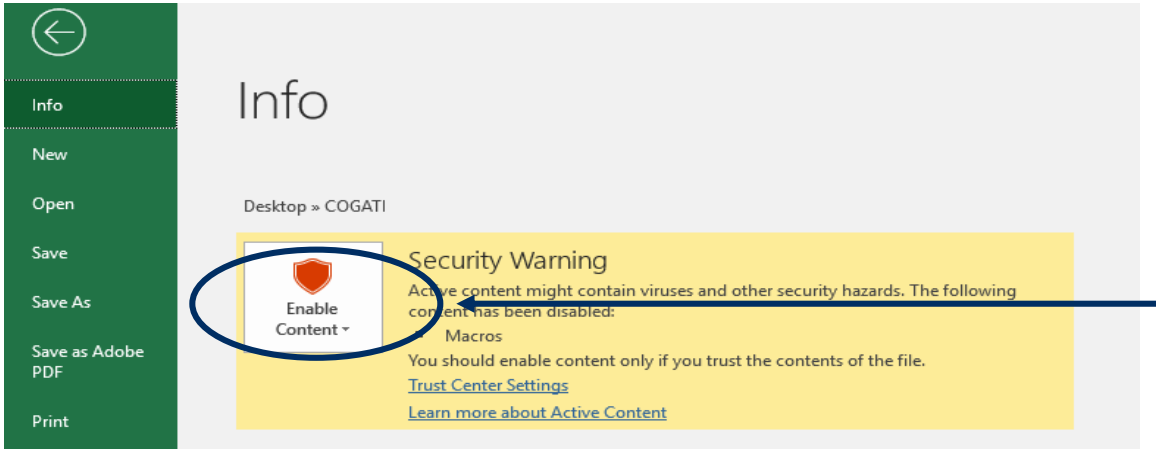
1. *Source: Mason, A.J., "OpenSolver – An Open Source Add-in to Solve Linear and Integer Progammes in Excel", Operations Research Proceedings 2011, eds. Klatte, Diethard, Lüthi, Hans-Jakob, Schmedders, Karl, Springer Berlin Heidelberg pp 401-406, 2012, http://dx.doi.org/10.1007/978-3-642-29210-1_64, http://opensolver.org*

Step 2: Enable Macros

When you open the model file, you need to enable macros to run. To do this EITHER:

Click enable content

OR



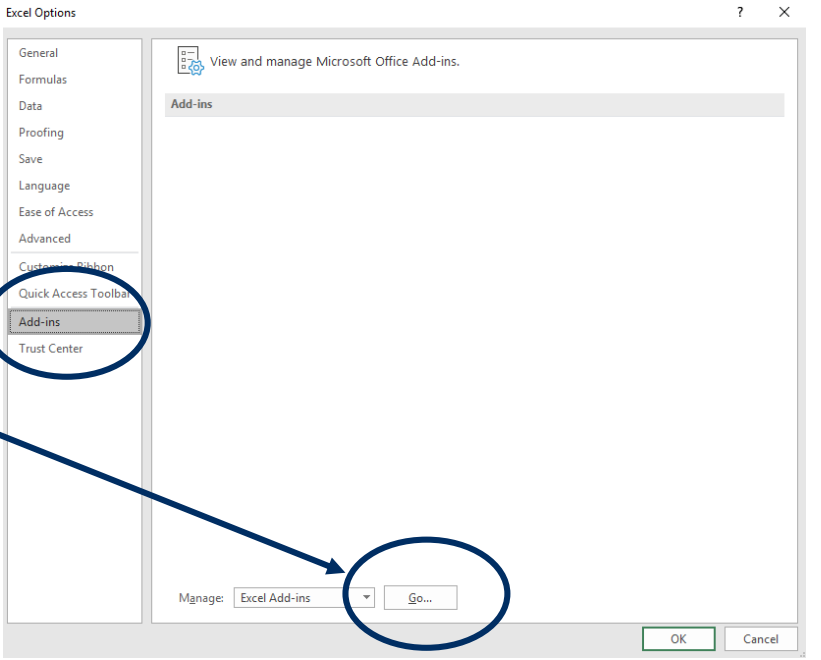
1. Click File
2. Click enable content

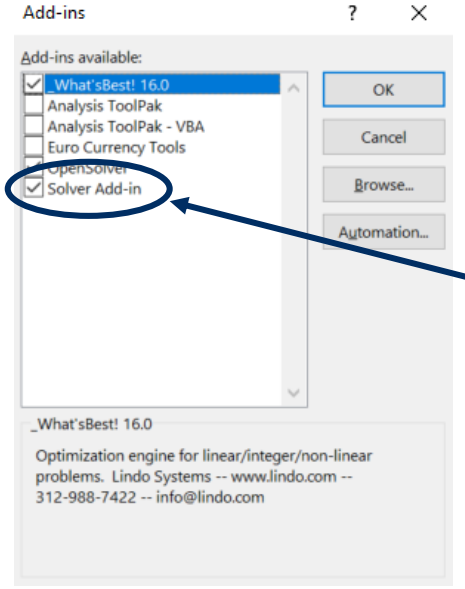
Step 3: Ensure the Excel Solver Add-in is Enabled

The Excel Solver Add-in should be available as standard on your version of Excel

1. Go to File -> Options -> Add-ins

2. Click “Go” to Manage Add-ins





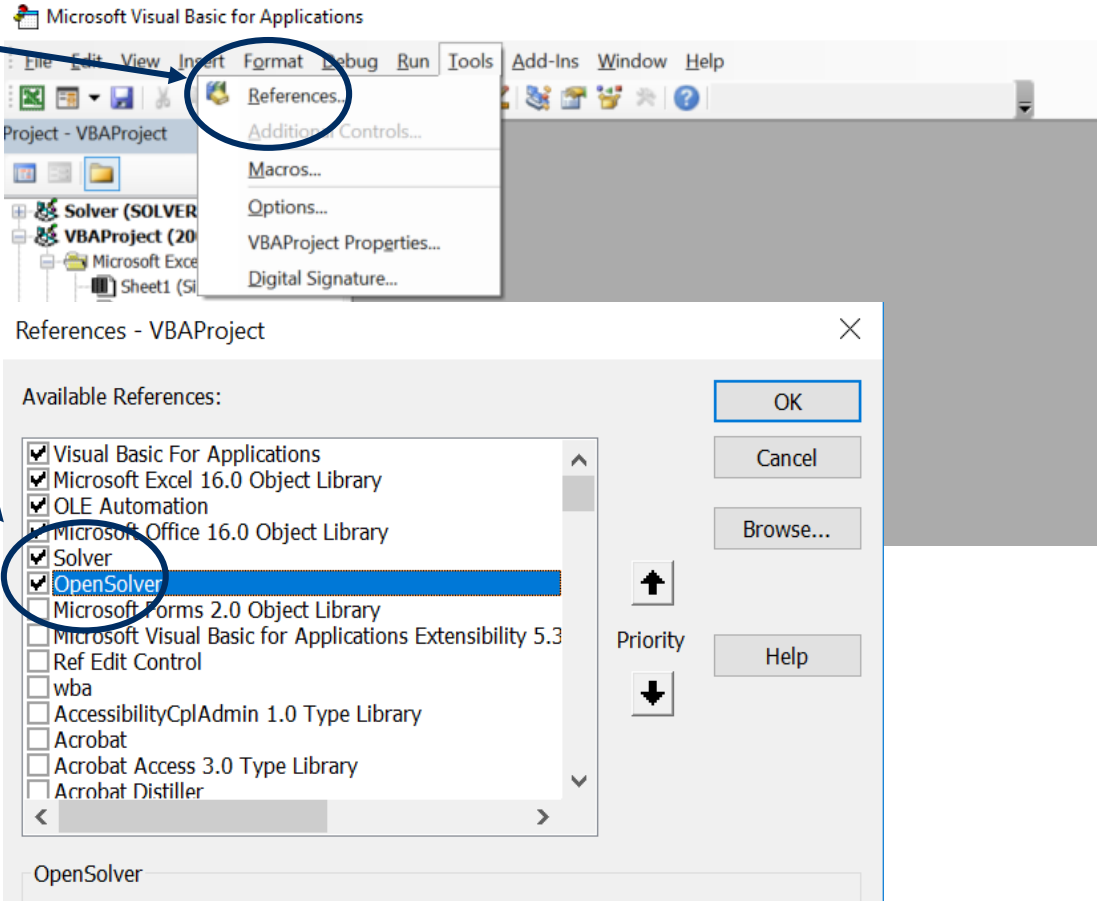
3. Tick the Solver Add-in

4. Click OK and exit from Options

Step 4: Enable the Macro to Run the Solver

In order to automatically run the solver, you will need to give permission for the model macro to run the add-in

1. Open Visual Basic for Applications by using the keyboard shortcut: ALT + F11
2. Go to Tools -> References
3. Tick the box related to your solver (in our case OpenSolver) **AND** the Solver boxes
4. Click OK
5. Exit Visual Basic



If Your Solver (or OpenSolver) Does Not Appear in the List of Available References or Appears As "Missing"…

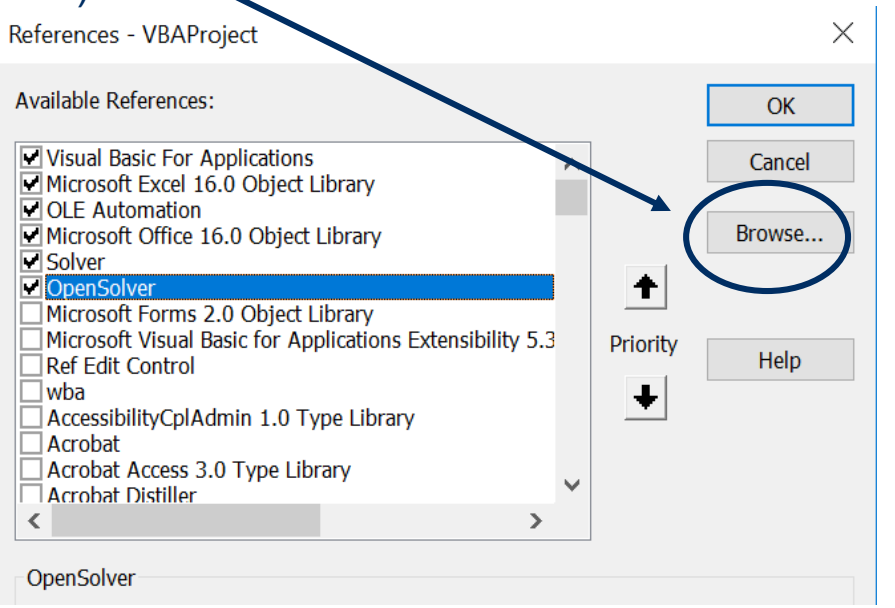
1. Click Browse and navigate to where you saved your solver, in our case OpenSolver, in the Folder in Step 1

2. Select your solver (e.g. "OpenSolver.xlam")

3. Click OK and ensure the box related to your solver (e.g. OpenSolver) box is ticked

4. Click OK

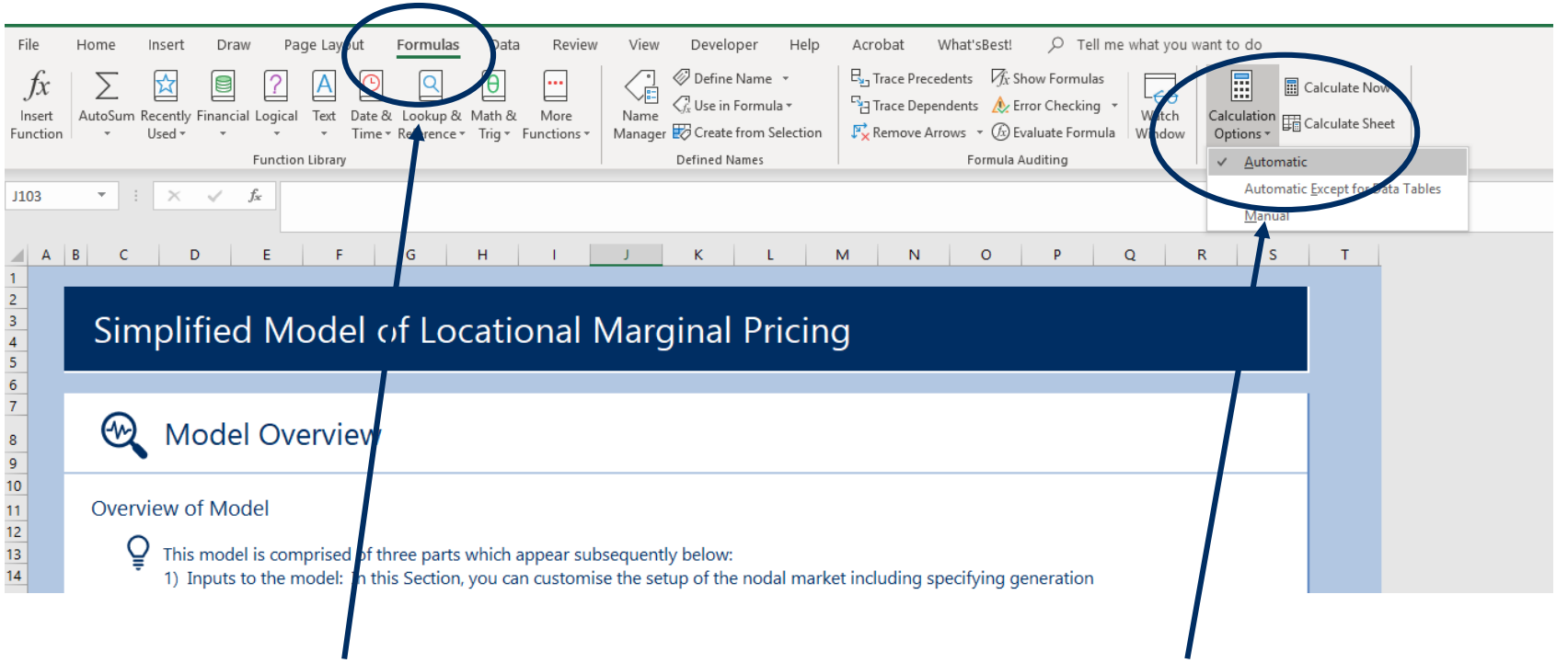
5. Exit Visual Basic



You may need to repeat this step if you later change the file location of your solver

Step 5: Make Sure Calculations are Set to Automatic

Automatic calculations are required for the solver to run, and for the dynamic aspects of the model to function



1. Click Formulas on the Ribbon

2. Go to Calculation Options and Select Automatic

You’re ready to go!

1 Overview of Model

Purpose of the Model

The model illustrates how the mechanics of locational marginal pricing and financial transmission rights work using a simplified model

What does the model do?

- The model illustrates the calculation of locational marginal prices (LMPs) for a simplified network
- The model illustrates the influence of congested transmission constraints on the calculation of LMPs
- The model allows the user to examine the financial outcomes for generators within the simplified model
- The model illustrates how financial transmission rights (FTRs) would change the financial outcomes for generators

What does the model not do?

- The model is not representative of the National Electricity Market
- The dispatch engine is simplified and the results represent a simplified dispatch pattern
- The model does not explain differences between the current market operation and the reform
- The model does not explain how FTRs are distributed or sold

Structure of the Simplified Model

The model is comprised of three panels

Model Inputs

In this section, you can customise the setup of the nodal market including specifying generation capacities and load at each node, as well as transmission capacity connecting the nodes. After setting inputs, loading a scenario, or choosing to randomise inputs, you may then solve the model.

Model Results

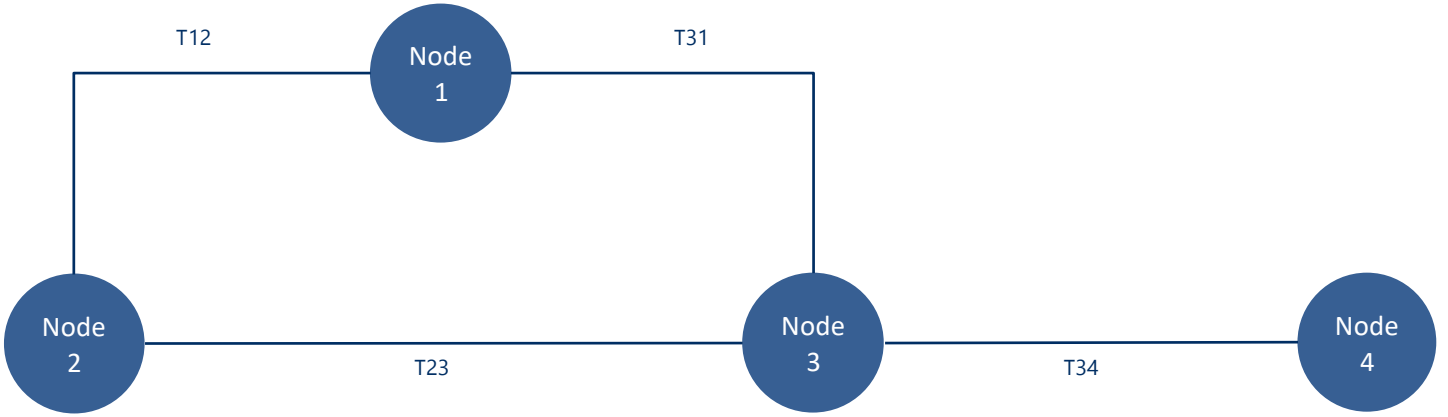
In this section, you can review the results from the model run. In particular, you can see the outturn LMPs, volume weighted average price (VWAP) as well as generation, load, and flows across/between nodes. In addition, you can examine a node in detail.

Generator Financial Outcomes

In this section, you can examine the financial outcomes for any generator in the model. You can see the FTR pay-outs resulting from the model run, as well as the calculation of settlement residue. You can also choose the size of the generator, where it is located, and examine how contract market positions and holding FTRs affects the financial outcomes for the generator.

The Network Typology in the Model

The model is comprised of four nodes connected by four transmission lines

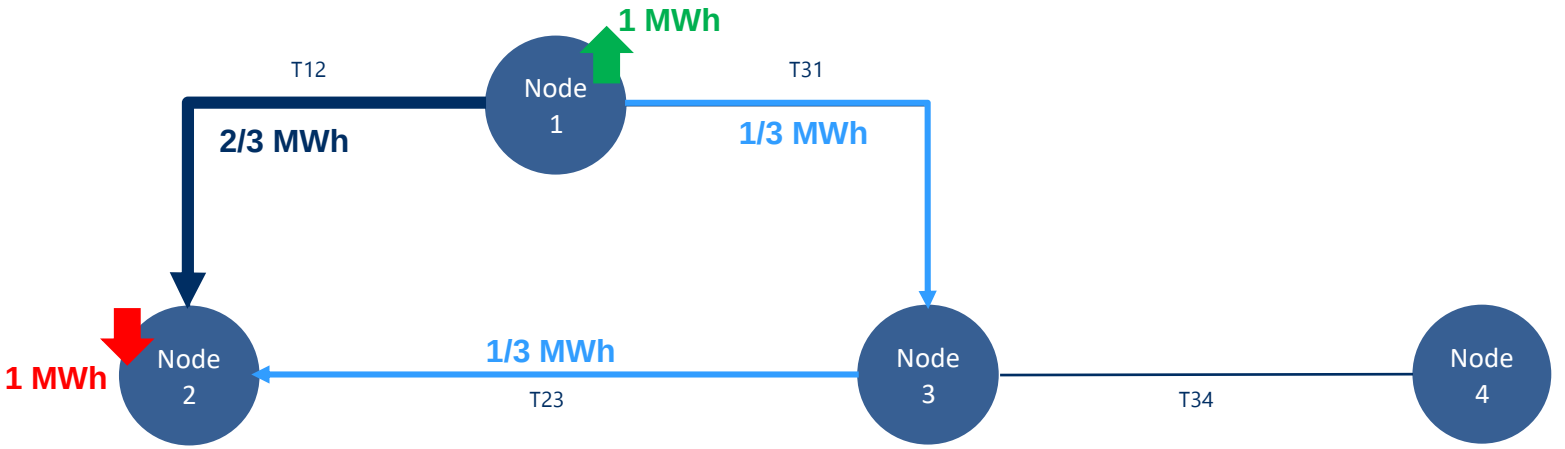


Key Model Assumptions

- Each node may contain generation and/or load
- There are three fuel types of generation allowed in the model, each with their own marginal cost of generation
- All generators are assumed to bid the marginal cost of generation which determines how they are dispatched
- Transmission is lossless, but power flows obey Kirchhoff's law
- The Value of Lost Load is set at $15,000 per MW

Power Flows

Power flows in the model obey Kirchhoff's Law



Explaining Model Power Flows

- Suppose that **1 MWh** of power is injected at Node 1 to meet **1 MWh** of load at Node 2
- We assume that each transmission line in the model has equal characteristics other than capacity (e.g. reactance is the same)
- Power faces twice the "resistance" flowing from Node 1 to Node 2 via Node 3 than flowing directly from Node 1 to Node 2
- Therefore, for every 1 MWh of power injected at Node 1 and taken off at Node 2:
  - **2/3 MWh** flows on T12 from Node 1 to Node 2; and
  - **1/3 MWh** flows from Node 1 to Node 2 via Node 3

Model Prices

There are two main sets of prices calculated in the model

Locational Marginal Prices (LMP)

The locational marginal price or LMP is determined at each node and is set by the system marginal cost to serve an additional 1 MW of load at the node:

- If load at Node 1 is 100 MW, then the LMP is the additional cost that would be incurred to serve 101 MW of load at Node 1
- If load at Node 1 is 0 MW, then the LMP is the additional cost that would be incurred to serve 1 MW of load at Node 1

Volume Weighted Average Price (VWAP)

The volume weighted average price or VWAP is set for the entire system (because our model contains only one region) and is calculated as a load-weighted average of LMPs across nodes.

Formally:

$$\text{VWAP} = \frac{(\boldsymbol{Load\ @\ Node\ 1\ x\ LMP\ @\ Node\ 1}) + (\boldsymbol{Load\ @\ Node\ 2\ x\ LMP\ @\ Node\ 2}) + \ldots + (\boldsymbol{Load\ @\ Node\ 4\ x\ LMP\ @\ Node\ 4})}{(\boldsymbol{Load\ @\ Node\ 1} + \boldsymbol{Load\ @\ Node\ 2} + \ldots + \boldsymbol{Load\ @\ Node\ 4})}$$

2 Model Inputs

Model Inputs

You can customise the set-up of the model in four ways

1. You can customise the name and marginal cost of the three generation fuel types

Fuel Type	Marginal Cost ($/MW)
Solar	0
Coal	10
Gas	20

- The fuel types will be displayed in the order you enter them, so it may be beneficial to enter them in ascending order of marginal cost;

2. You can customise the generation capacity of each generation fuel type at each node

	Generation Capacity (MW)			
Fuel Type	Node 1	Node 2	Node 3	Node 4
Solar	500	500	0	200
Coal	0	0	0	0
Gas	0	0	0	0
Total (MW)	500	500	0	200

- VoLL will result in the system when there is insufficient generation capacity to meet load. Therefore, you may wish to enter generation capacity alongside load at each node to ensure there is sufficient capacity in the system.

Throughout the model, you can customise inputs or outputs in any cell that has this formatting and when you see this icon

Model Inputs

You can customise the set-up of the model in four ways

3. You can customise the load at each node

	Node 1	Node 2	Node 3	Node 4
Load (MW)	200	500	200	200

- VoLL will result in the system when there is insufficient generation capacity to meet load. Therefore, you may wish to enter load alongside generation capacity at each node to ensure there is sufficient capacity in the system.

4. You can customise the transmission capacity of each transmission line

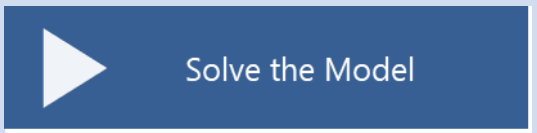
	T12	T23	T31	T34
Capacity (MW)	300	0	300	300

- The power flow constraints of the model assume that all lines have some transmission positive transmission capacity

Throughout the model, you can customise inputs or outputs in any cell that has this formatting and when you see this icon

Macros Following the Input Panel

After the input panel there are three options to run macros



- Clicking “Solve the Model” will solve model with your current inputs in the input panel

- Clicking “Randomise the Inputs” will replace the inputs in the input panel with random numbers
- The randomisation will not impact the names of generation fuel types or their marginal costs

- Clicking “Clear Current Inputs” will clear the input panel
- Clearing current inputs will not impact the names of generation fuel types or their marginal costs

The results of the model run will show automatically in the following results panels

3 Model Results

How the Model Solves and Displays Prices

The model calculates LMPs by minimising the cost of dispatch for the system whilst respecting generation and transmission capacity constraints and meeting load

Locational Marginal Prices (LMPs)

	Node 1	Node 2	Node 3	Node 4
LMP ($)	7,000	0	14,000	14,000
Load (MW)	200	500	200	200

Volume Weighted Average Price (VWAP) ($)	6,363.64

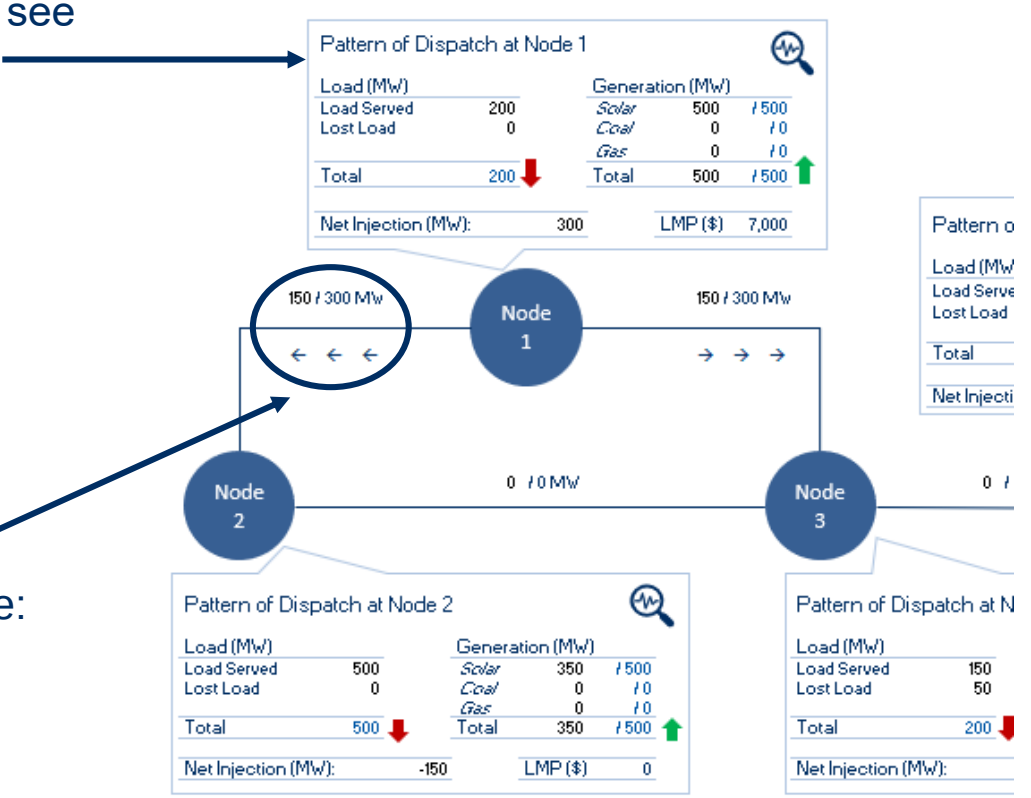
- After you have clicked “Solve the Model”, the LMPs and VWAP are displayed in the first results panel named “System Prices”
- The LMP shows the price of serving an additional 1 MW of load at each node
- The VWAP takes a load-weighted average of LMPs across nodes
- The LMPs should all be equal unless a transmission constraint binds
- An LMP of $15,000 per MW indicates VoLL, and that there is not enough generation to meet load at a given node

The full optimisation problem that solves the model is shown in the Appendix of this user guide

The Pattern of Dispatch Panel

The pattern of dispatch panel shows generation, met and lost load, and net injections at each node, as well as power flows around the system

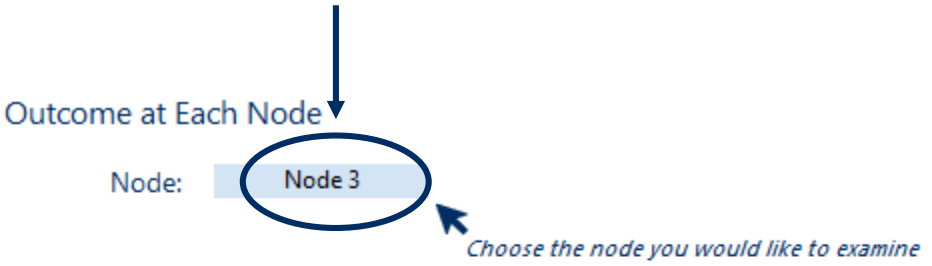
- In each “Pattern of Dispatch Box”, see for each node:
  - Load served and lost
  - Generation across fuel types
  - Net injection to the system
  - LMP
- For each transmission line, see the:
  - Total power flow
  - Direction of power flow



The “Outcome at Each Node” Panel

You can review the outcome at each node in more detail using this panel

1. Select the node you would like to examine using the drop down list



Locational Marginal Price ($)			20

Generation (MW)	MC ($)	Gen.	Capacity
Solar	0	0	0
Coal	10	0	0
Gas	20	0	0
Total		0	0

Load (MW)	
Load Served	0
Lost Load	0
Load	0

Net Injection (MW):	0

2. View information about the outcome of the node here

4 Scenarios

You Can Save or Load Scenarios Using the Scenario Editor Panel

You can store up to 50 custom scenarios

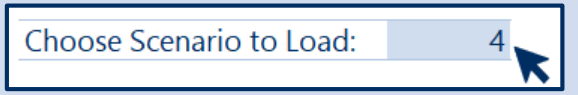
To Save Scenarios

- Enter a scenario description
- Click the save scenario button:

- The current inputs to the model will be saved in My Scenarios alongside a scenario number
- If you already have 50 scenarios stored, new scenarios will overwrite scenario 50

To Load Scenarios

- Choose a scenario to load using the drop down. You can view the scenarios description underneath:

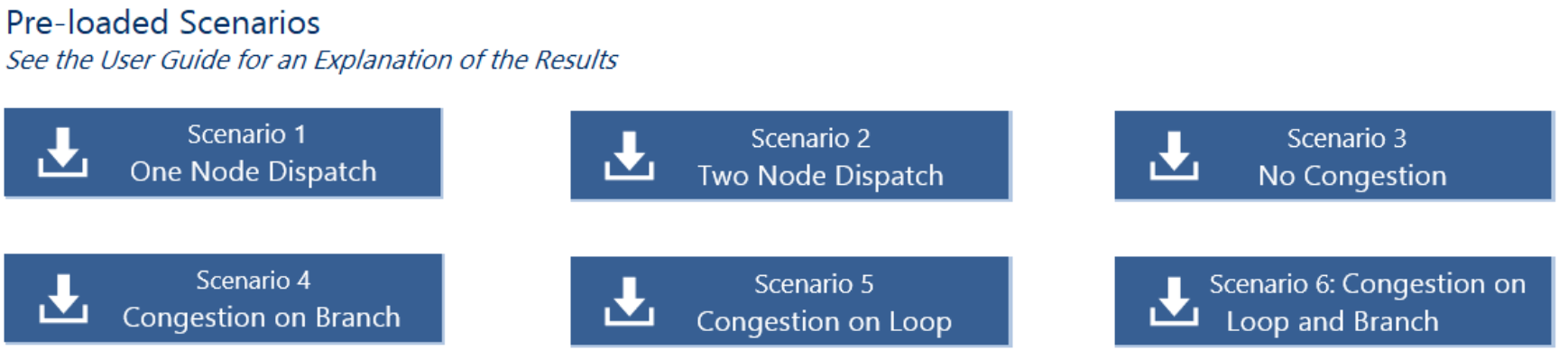


- Click Load scenario to automatically populate the inputs to the model with those in the scenario:

You can view and clear your custom scenarios in the “My Scenarios” sheet

We have Included Six Pre-Loaded Scenarios

To load the scenarios, click the relevant scenario in the pre-loaded scenarios panel to automatically load the model inputs



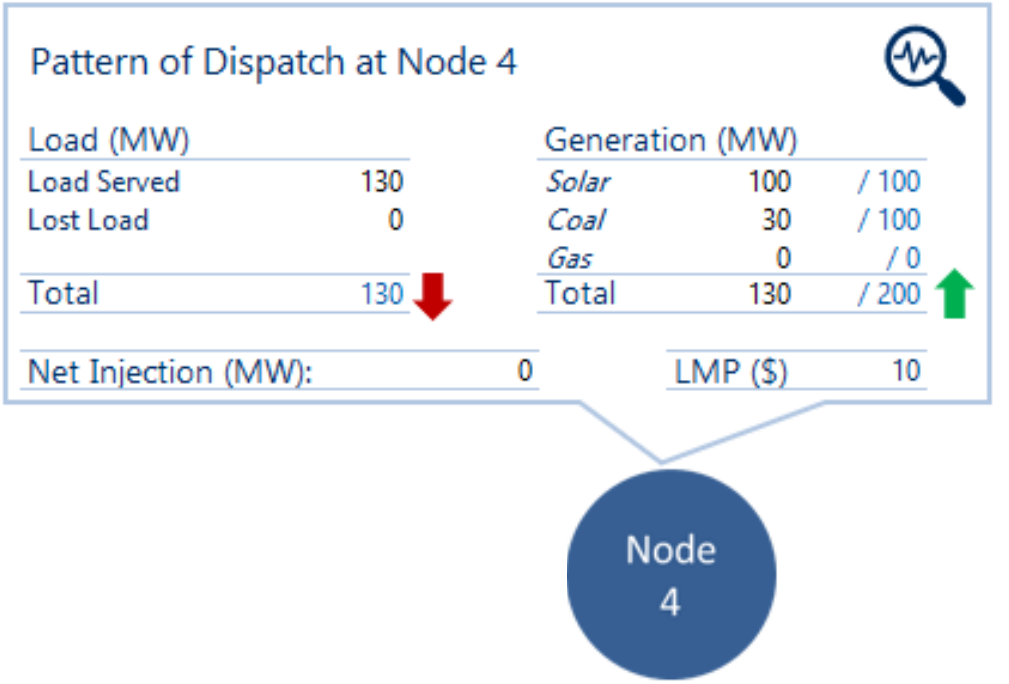
After loading custom or pre-loaded scenarios, you will need to solve the model!

Scenario 1: One Node Dispatch

Scenario 1
One Node Dispatch

Scenario 1 examines the pattern of dispatch with generation and load only at Node 4

- Scenario 1 considers load and generation only at one node: Node 4
- Node 4 has both 100 MW of solar and coal generation with marginal costs of $0 and $10 per MW respectively
- Node 4 has 130 MW of load
- The LMP at Node 4 is set by the cost of meeting an additional 1 MW of load (or the 131st MW of load)
- An additional 1 MW of load is most cheaply met by coal generation
- Therefore, the LMP at Node 4 is $10

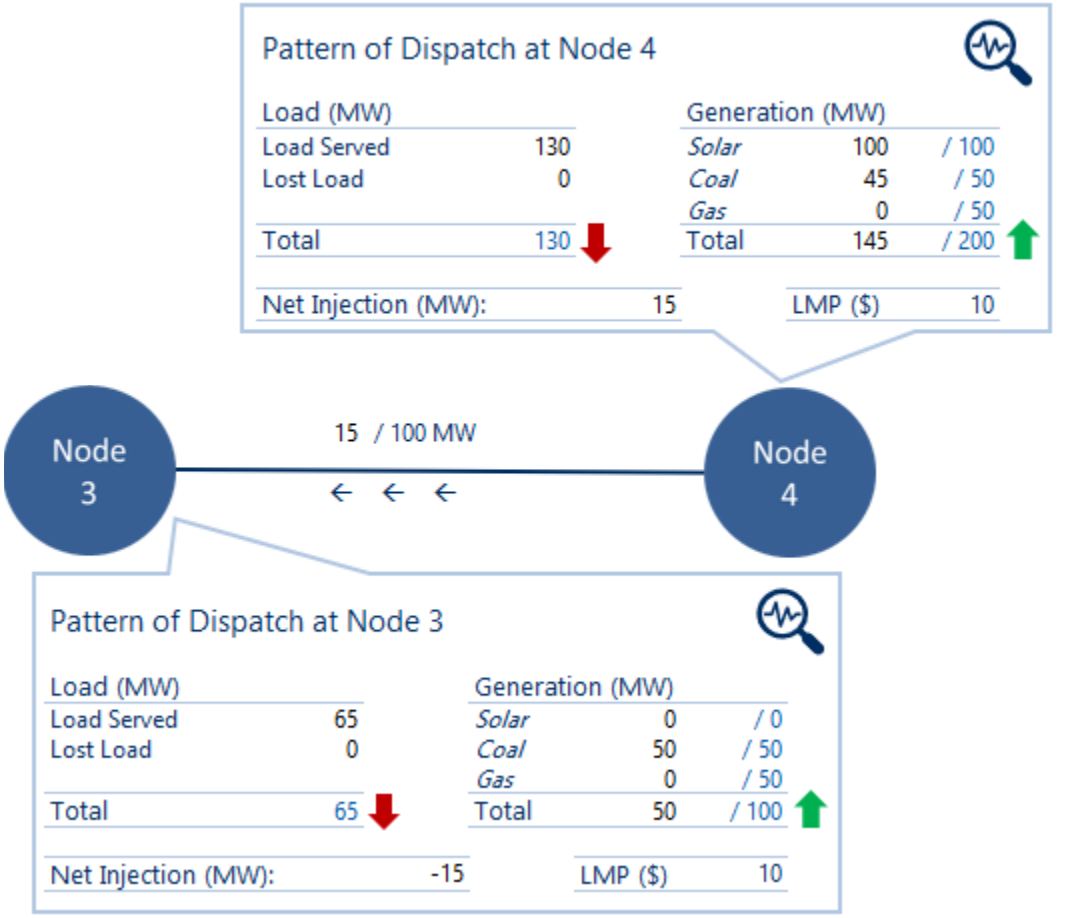


Scenario 2: Two Node Dispatch

Scenario 2
Two Node Dispatch

Scenario 2 examines the pattern of dispatch across generation and load at Node 3 and Node 4

- Scenario 2 considers load and generation at two nodes: Node 3 and Node 4
- Both Nodes have 50 MW of generation capacity of coal and gas, but Node 4 also has 100 MW of generation capacity of solar
- Node 4 has 65 MW of load and Node 4 has 130 MW of load
- An additional 1 MW of load at both Nodes is most cheaply met by coal generation at Node 4
- Therefore, the LMP at both Nodes is $10
- Instead of using more expensive gas generation to meet load at Node 3, power flows from Node 4 where it is more cheaply generated using coal generation

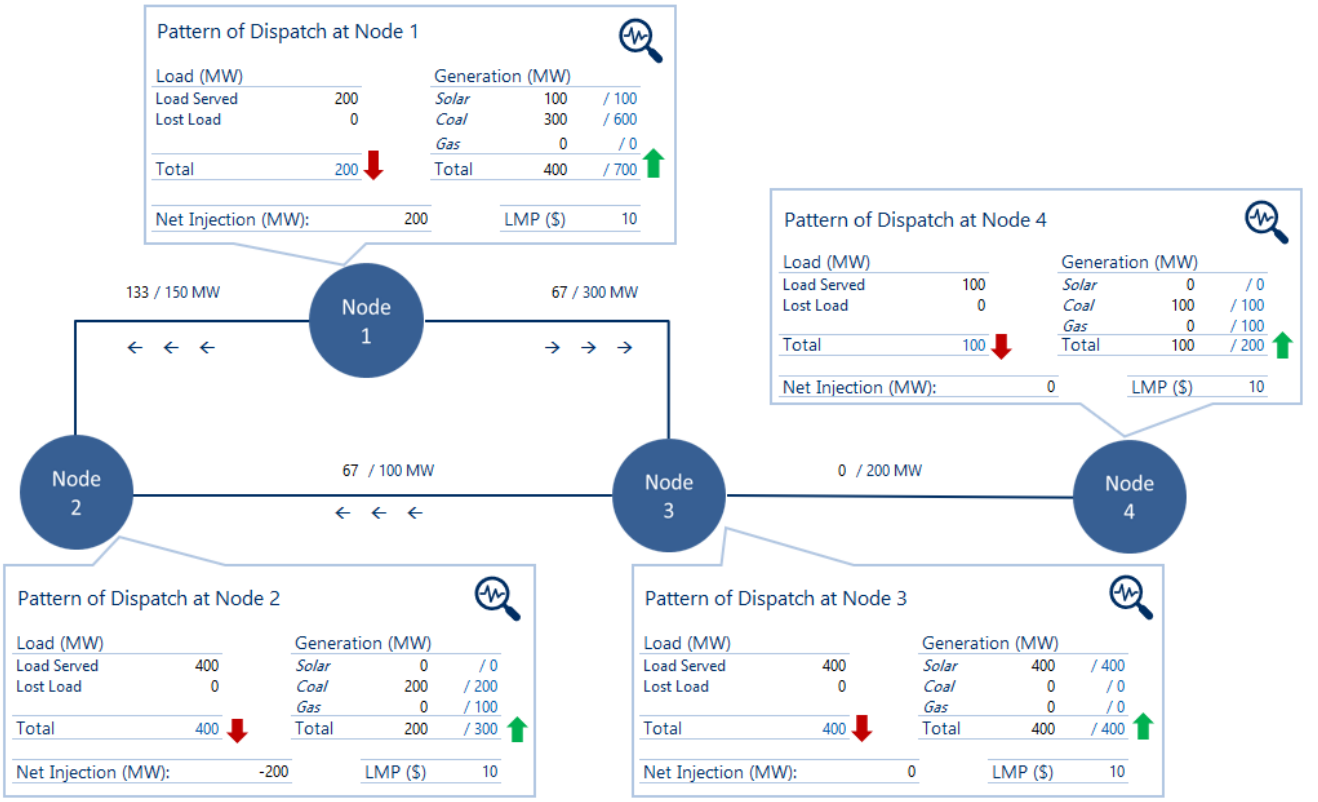


Scenario 3: No Congestion

Scenario 3
No Congestion

Scenario 3 examines the pattern of dispatch across the entire system, where there is no congestion

- An additional MW of load is most cheaply met by one MW of power generated by coal which has MC of $10
- Therefore, the LMP is $10 across the system
- Node 1 injects 200 MW of coal generated power to most cheaply serve load at Node 2
- Power flows obey Kirchhoff's Law:
  - Two thirds (133 MW) of the net injection flows on T12
  - One third (67 MW) flows on T13 and then T23

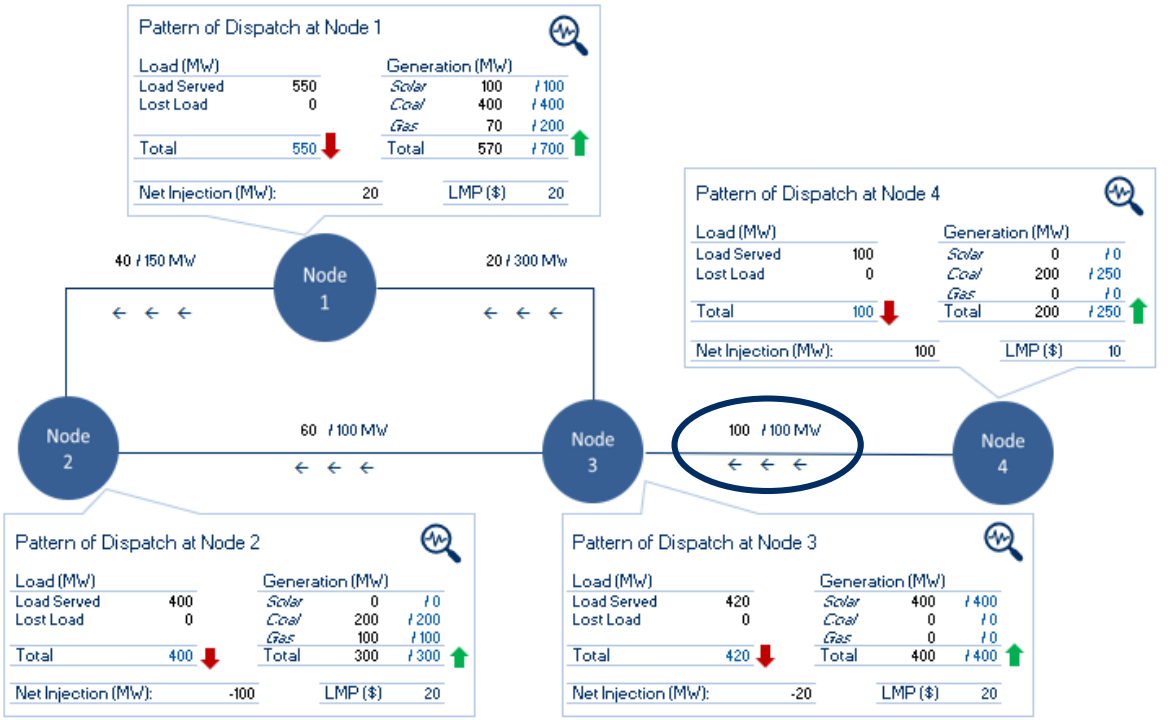


Scenario 4: Congestion on Branch

Scenario 4
Congestion on Branch

Scenario 4 examines the pattern of dispatch across the system but where there is congestion on the branch

- In this example, the line T34 has become congested
- An additional MW of load at Node 4 is most cheaply met by an additional MW of coal generation at Node 4 and therefore the LMP is $10 at Node 4
- An additional MW of load at Nodes 1, 2, or 3, would also be mostly cheaply met by an additional MW of coal generation at Node 4
- However, because T34 is congested, coal generation at Node 4 cannot be used to serve load at Nodes 1, 2 or 3
- Instead, an additional MW of load at Nodes 1, 2 or 3 must be met by an additional unit of gas generation at Node 1
- Therefore, the LMP at Nodes 1, 2 and 3 is $20

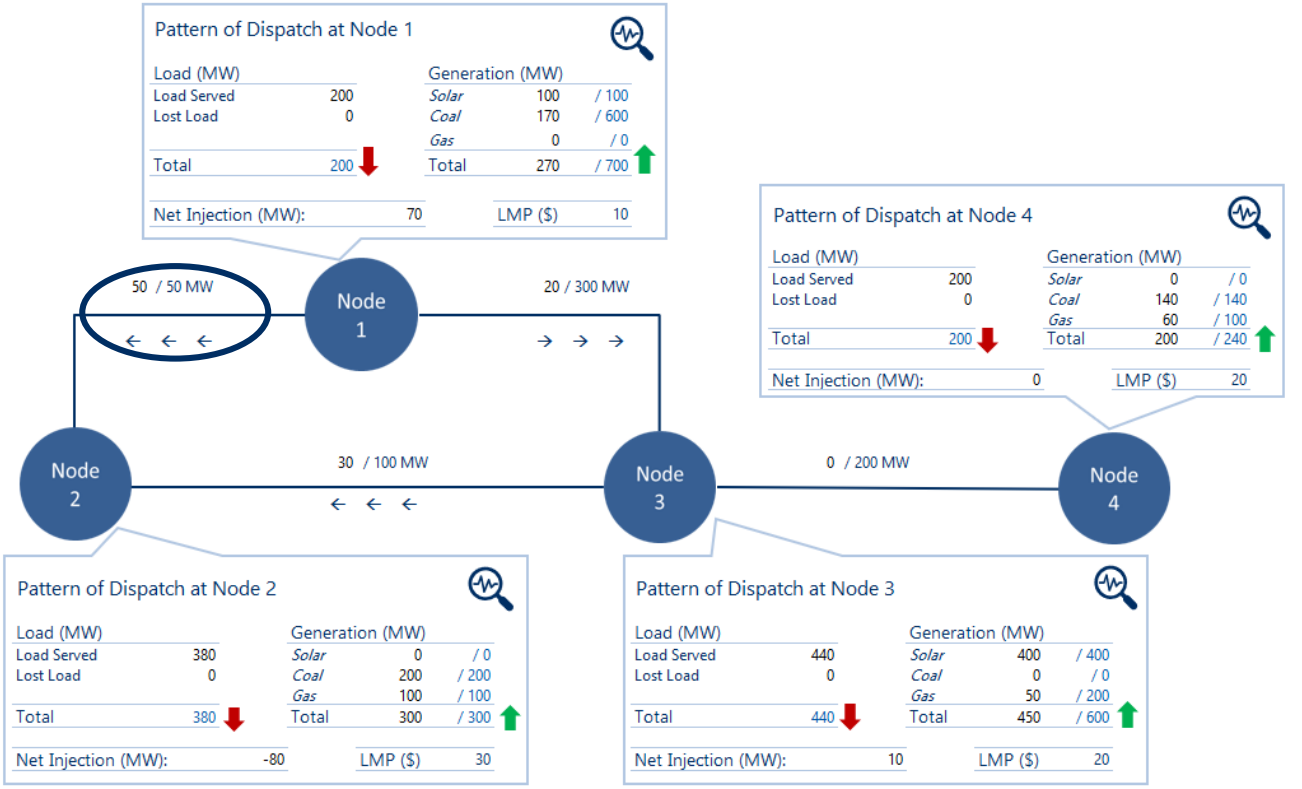


Scenario 5: Congestion on Loop

Scenario 5
Congestion on Loop

Scenario 5 examines the pattern of dispatch across the system but where there is congestion on the loop

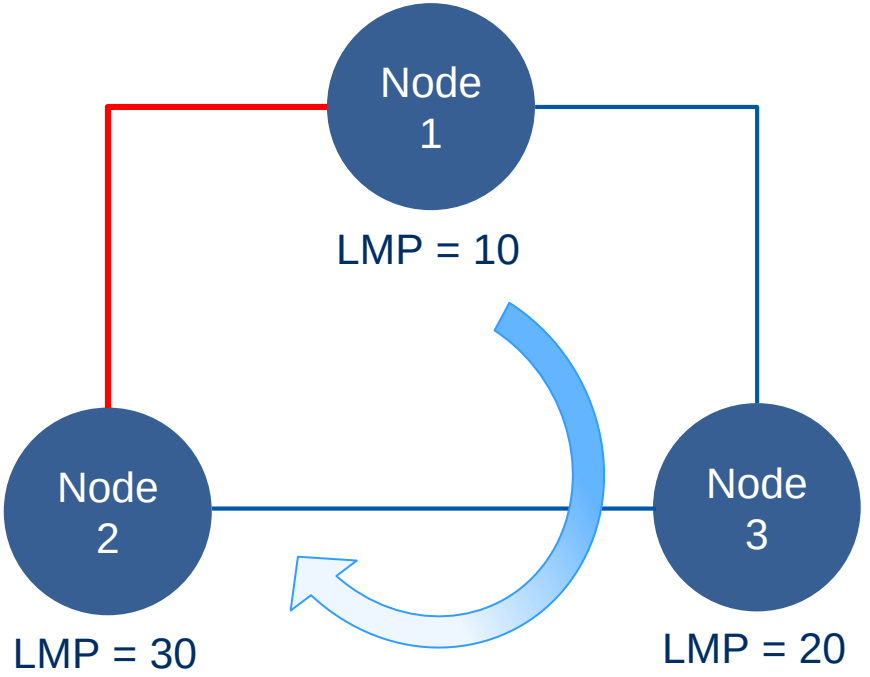
- Node 2 does not have enough generation to serve load
- The excess load is most cheaply served by coal generation at Node 1
- However, Node 1 cannot serve all the excess load, because the transmission line T12 becomes congested
- Instead, some excess load is served by gas generation at Node 3
- The LMPs differ across Nodes 1, 2, and 3



Scenario 5: Congestion on Loop

The Spring Washer Effect is caused by a congested line in a flow loop

- An additional MW of load at Node 1 would be served by coal generation at Node 1 and therefore the LMP = 10
- An additional MW of load at Node 3 would be served by gas generation at Node 3 and therefore the LMP = 20
- The additional MW of load at Node 2 cannot be served by the excess coal generation at Node 1 because one third of the net injection of power at Node 1 must flow on line T12 which is congested
- An additional MW of load at Node 2 can only be met by reducing the generation of coal by 1 MW at Node 1, and increasing the generation of gas by 2 MW at Node 3. Therefore the LMP = (2x$20) – (1x$10) = $30.
- In other words, coal generation at Node 1 must be backed off to reduce congestion on T12, so that one third of the net inject of power at Node 3 can flow on T12

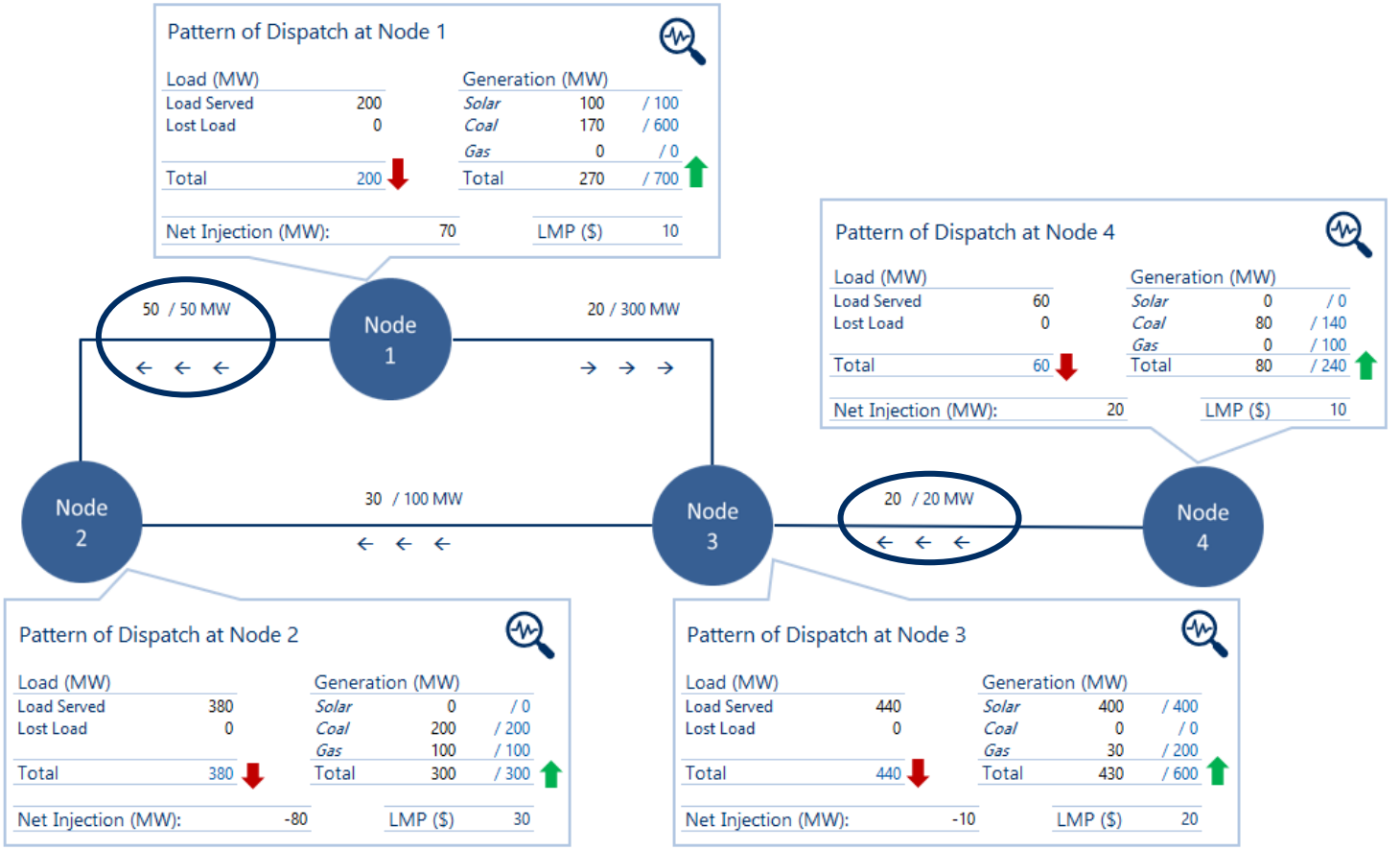


- The pattern of rising LMPs is similar to the shape of a spring washer
- The spring washer effect demonstrates that binding constraints in other parts of a meshed grid may influence an LMP at a node on the same grid, but not directly impacted by the congested line

Scenario 6: Congestion on Branch and Loop

Scenario 6: Congestion on Loop and Branch

Scenario 6 demonstrates a combination of Scenarios 4 and 5 with congestion on both the loop and branch resulting in differing LMPs across Nodes



5 Overview of Financial Outcomes Analysis

Financial Market Outcomes Panel

The financial outcomes panel allows you to examine the financial implications of each model run for generators across the system

- The settlement residue panel allows you to see total revenue from load paying VWAP and total cost from paying generation at LMP
- The difference between system revenue and system cost is the settlement residue in the dispatch interval

Settlement Residue

	Node 1	Node 2	Node 3	Node 4	Total
Load (MW)	200	380	440	60	1,080
VWAP ($)	21.1	21.1	21.1	21.1	21.1
Total Revenue ($)	4,222	8,022	9,289	1,267	22,800

	Node 1	Node 2	Node 3	Node 4	Total
Generation (MW)	270	300	430	80	1,080
LMP ($)	10	30	20	10	
Total Cost ($)	2,700	9,000	8,600	800	21,100

Settlement Residue ($)	1,700

- The FTR pay-outs panel displays the pay-outs of one-way FTRs implied by the model run
- The pay-out of an FTR is determined by the maximum of the difference in price between where the FTR is purchased to and from and zero, multiplied by the volume of power under the FTR
- The pay-out corresponds to the fair value of FTRs in the model run

FTR Pay-Outs and Fair Value ($)

From:	*To:*	VWAP
Node 1		11
Node 2		0
Node 3		1
Node 4		11

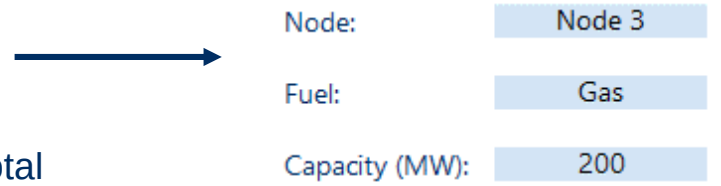
To:	*From:*	VWAP
Node 1		0
Node 2		9
Node 3		0
Node 4		0

We are illustrating the financial market outcomes panel using Scenario 6: Congestion on Loop and Branch

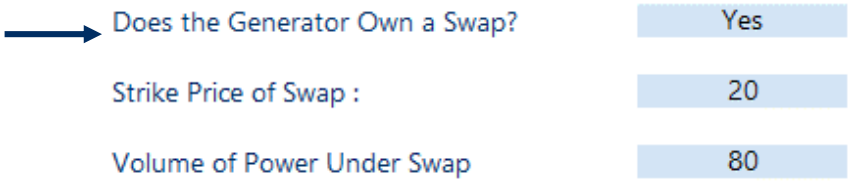
Generator Financial Outcomes

The generator financial outcome panel allows you to more closely examine the financial implications of a model run for one generator in the system

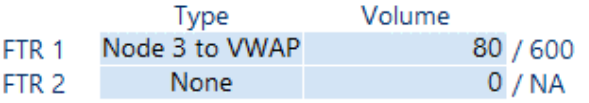
- To select the generator you would like to examine, choose the node, fuel type, and size/capacity of the generator
- Note that the size of the generator is limited by the total capacity of the fuel type at the node you select



- Then choose if the generator owns a baseload swap in the forward market
- Choose the strike price of the swap and the volume contracted
- The pay-out of the swap is determined by the difference between the strike price of the swap and the VWAP, multiplied by the volume of power under the swap



- Lastly, choose if the generator owns one or two FTRs, and the volume contracted under each FTR
- FTRs are continuous, one-way FTRs



Simulated Financial Outcomes

You can then simulate the financial outcomes for your chosen generator, with chosen FTRs and swaps over five dispatch intervals with varying loads

1. Choose how load varies across the hours using the drop down buttons

2. Simulate the model

	Run 1	Run 2	Run 3	Run 4	Run 5
Load	-5%	10%	5%	-10%	-5%

Simulate the Model

	Base Run	Run 1	Run 2	Run 3	Run 4	Run 5
Generation Capacity (MW)	200	200	200	200	200	200
Percentage Dispatched	15%	0%	75%	45%	0%	0%
Generation (MW)	30	0	150	90	0	0
LMP ($)	20	15	20	20	15	15
Generation Revenue ($)	600	0	3,000	1,800	0	0
Generation Cost ($)	600	0	3,000	1,800	0	0
Profit ($)	0	0	0	0	0	0
Pay-Out on Swap	-89	356	-89	-89	356	356
Pay-Out on FTR 1 ($)	89	44	89	89	44	44
Pay-Out on FTR 2 ($)	NA	NA	NA	NA	NA	NA
Profit Without FTR ($)	-89	356	-89	-89	356	356
Profit With FTR ($)	0	400	0	0	400	400

3. Examine the financial outcomes in the table and in the two charts below

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Appendix

Technical Appendix Outlining the Optimisation Problem

The Optimisation Problem

The model dispatches the system by minimising the costs of generation subject to a number of constraints

Objective function: $\min_{G_i^k, X_{ij}} \sum_k \sum_i MC^k G_i^k$

Where i is the node, k is the type of generation fuel, MC^k is the marginal cost of generation fuel type k, and G_i^k is generation of fuel type k at node i. X_{ij} is an "export" of power from node i to node j where $i \neq j$. The available fuel types of generation include VoLL. We add a small penalty in the objective function for total transmission flows to prevent unnecessary flows arising because transmission is lossless – this penalty is not shown here for brevity.

Minimised subject to the following constraints:

- Power delivered (incl. VoLL) meets load at every node → $\forall\, i:\ Load_i = Power_i\left(G_i^k, X_{ij}\right)\ \ \forall\, i,k,j;\ i \neq j$
- Generation across the system (incl. VoLL) must meet load ⟶ $\sum_i Load_i = \sum_k \sum_i G_i^k$
- An "export" of power from one node to another cannot be negative ⟶ $\forall\, i,j;\ \ i \neq j:\ \ X_{ij} \geq 0$
- Total flows on each line (as dictated by Kirchhoff's Law) must not exceed the capacity of the line. ⟶ $\forall m:\ \ T_m \geq f\left(\sum_j \sum_i X_{ij}\right)\ \ \ \forall i,j;\ i \neq j$
- Generation of each fuel type at each node cannot exceed capacity ⟶ $\forall k,i\ :\ \ G_i^k \leq \overline{G_i^k}$

Where T_m is the transmission capacity of line m and $\overline{G_i^k}$ is the generation capacity of fuel type k at node i. f(.) is a function that maps exports to power flows using Kirchhoff's law. $Power_i\left(G_i^k, X_{ij}\right)$ described total power at node i as a function of generation and net injections.

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