Assessing Power System Flexibility with IRENA FlexTool

Hands-on 2

Please use the following citation for:

- **This exercise**

Plazas-Niño, F. Hoseinpoori P., Kell A., & Hawkes A. (2025, April). Hands-on 2: Assessing power system flexibility with IRENA FlexTool (Version 1.0.). Climate Compatible Growth. DOI: 10.5281/zenodo.17070391

- **FlexTool software**

IRENA. (2024). FlexTool (Version v2.0.0). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_FlexTool_v_2_0.zip

- **FlexTool Forum**

Please sign up to the help forum here. If you are stuck, please ask questions here. If you get ahead, please answer questions in the same forum. Please state that you are using the version 2.0.

Learning outcomes

By the end of this exercise you will be able to:

1) Run a demo model.

2) Understand the inputs of a demo model.

3) Understand the results of a demo model.

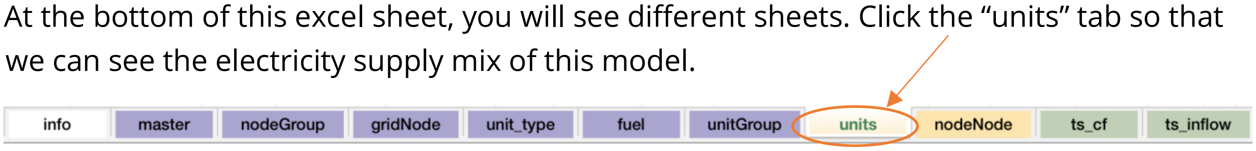
4) Adjust the inputs of a model.

Investigating and running the demo model

In this activity, we want to investigate and run the demo model which comes with FlexTool. To do this, open the following excel file at the location that you downloaded FlexTool:

“inputData\demoModel-1.xlsm”

At the bottom of this excel sheet, you will see different sheets. Click the “units” tab so that we can see the electricity supply mix of this model.



You will now be presented with the units which make up this model. We can see that this model is made up mainly of fossil fuel-based electricity generation, with some hydro power in nodeB, wind power in node C, and small shares of PV and biomass in most nodes.

We can see that

- nodeA has 500 MW of coal capacity, 200 MW of oil, 30 MW of biomass amongst others.
- nodeB has 150 MW of Hydro_RES (reservoir hydro), 120 MW of Hydro_ROR (run of river hydro) and 150 MW of oil amongst others.
- nodeC has 500 MW of coal capacity, 300 MW of natural gas engine capacity, 200 MW of oil and 150 MW of wind amongst others.

The Figure below shows the electricity mix for nodeA.

		Choose one input option (none, fuel, cf profile, inflow **or** input grid+node)					Output #1		
unitGroup	unit type	fuel	cf profile	inflow	input grid	input node	output grid	output node	capacity (MW)
Coal	ST_coal	coal					elec	nodeA	500
Oil	CC_oil	oil					elec	nodeA	200
Bio	ST_bio	biomass					elec	nodeA	30
Wind	wind		wind_A				elec	nodeA	0.01
PV	PV		PV				elec	nodeA	15
Battery	battery						elec	nodeA	0.01

Next, we want to run the model. To do this, open the following file in the topmost model folder:

flexTool.xlsm

Once this is opened, click the “Sensitivity scenarios” sheet. This is shown below.

Next, we want to ensure that the demoModel-1.xlsm model is in the “Active input files” column, and that the “template.xlsm” isn’t. To do this, click the light green “<->” button to toggle the location of the input files.

This tells FlexTool which of the input files to run.

The table should look like the following:

Active input files:		Inactive input files:
	<->	template.xlsm
	<->	
demoModel-1.xlsm	<->	
	<->	
	<->	demoModel-2-2017.xlsm
	<->	demoModel-2-2030.xlsm
	<->	
	<->	template-EVs.xlsm

We also need to ensure that the active scenario is set to "Base". This scenario does not add any additional constraints to the model, allowing it to run as-is.

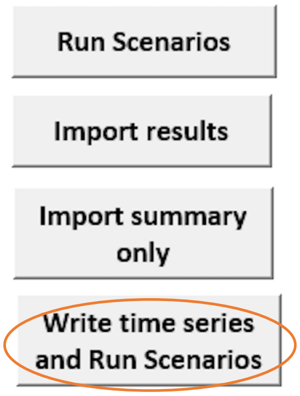
Once again, click the light green "<->" button to toggle the location of the scenarios. This tells FlexTool which scenarios to run.

Later, we will see how to run multiple scenarios at once by moving the desired scenarios to the left side using the same process.

At this stage, the table with scenarios should look like the following:

Active scenarios:		Inactive scenarios:
Base	<->	
	<->	Invest
	<->	
	<->	demo1_invest_transCap
	<->	demo1_invest_genCap
	<->	demo1_invest_storages
	<->	demo1_invest_all
	<->	
	<->	demo2_storages
	<->	demo2_PV
	<->	demo2_windGas
	<->	
	<->	
	<->	template_storageMW
	<->	template_storageFree
	<->	template_changeDemand
	<->	template_changeTransferCapacity
	<->	
	<->	

Once we have selected demoModel-1, we can run the model. To do this, click the "write time series and Run scenarios button" in the top left of the sheet:



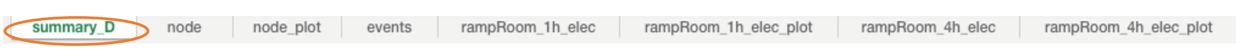
A “cmd” box should open, which means that FlexTool is running. Once FlexTool has run, a excel results spreadsheet will open called “Results_YEAR_MONTH_DAY_HOUR_MINUTES”, with the respective date and time that you run the model.

Note: Please ensure that Macros and ActiveX controls are enabled for the Flextool file to function properly.

In the next activity we will see how we can interpret the results.

Quick check of flexibility issues

Now that we have the results, we want to see whether there are any issues with regards to flexibility in this system. To do this, we should check the “summary_D” tab of the results spreadsheet, as shown below.



Once we have opened “summary_D”, we see a lot of information relating to our run, as can be seen below.

22	General results	elec
23	VRE share (% of annual demand)	8.554
24	Loss of load (% of annual demand)	2.368
25	-> ramp up constrained (% of annual demand)	0
26	Excess load (% of annual demand)	0
27	Insufficient reserves (% of reserve demand)	0
28	Insufficient inertia (% of inertia demand)	
29	Curtailment (% of VRE gen.)	-6.66E-06
30	-> ramp down constrained (% of VRE gen.)	0
31	Peak load (MW)	2101.55
32	Peak net load (MW)	1946.3
33		
34	Flexibility issues	elec
35	Loss of load (max MW)	255.475
36	Excess load (max MW)	0
37	Reserve inadequacy (max MW)	0
38	Insufficient inertia (TWs/a)	0
39	Curtailment (max MW)	0.000137541
40	Curtailment (TWh/a)	-7.48E-08
41	Model leakage (TWh/a)	0
42	Capacity inadequacy (max MW)	0
43	Spill (TWh/a)	0

First, we see that the variable renewable energy share (VRE) as a percentage of demand is over 8.5%. However, we can also see that we have a loss of load of over 2%. This is amount of loss of load is notable, and so we need to find out where and why we have this.

We see a very minor about of curtailment, which isn't a real issue in this case, and no further flexibility issues.

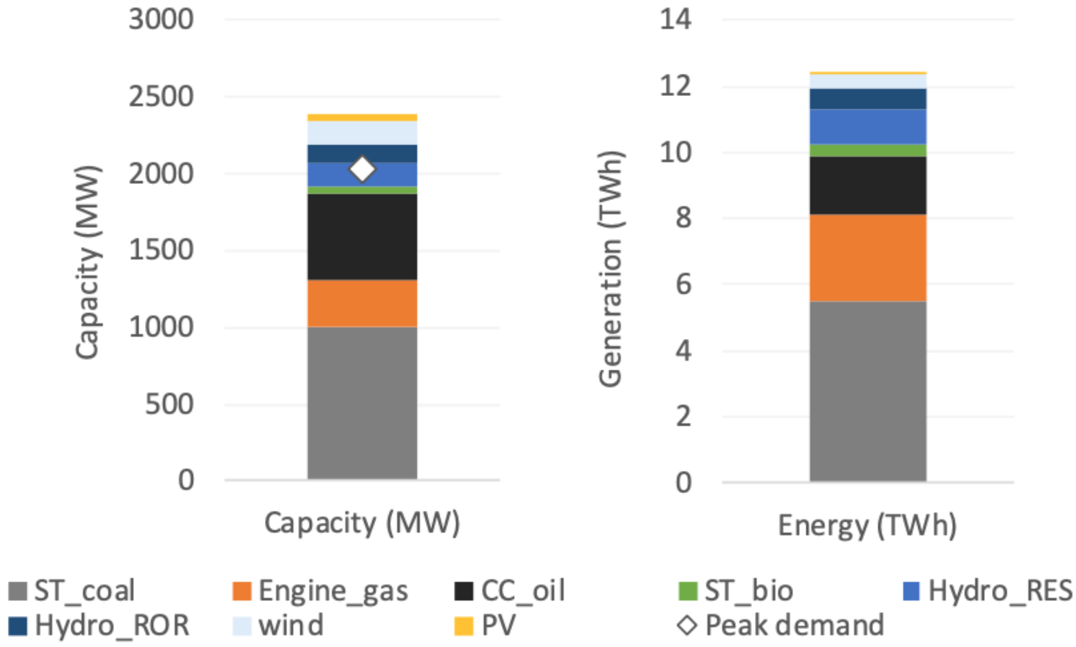
If you would like to see understand the meaning of the rest of the results, open the result file to see definitions for each.

Investigating loss of load

We want to find out where this loss of load is coming from. So, to achieve this, we will begin to investigate the results from FlexTool.

The loss of load may be due to the capacity in the system.

First, plot the capacity and energy of each of the different unit types. This data can be found in the "summary_D" sheet, between rows 81 and 104. With the peak demand being displayed at row 31. An example is shown below:

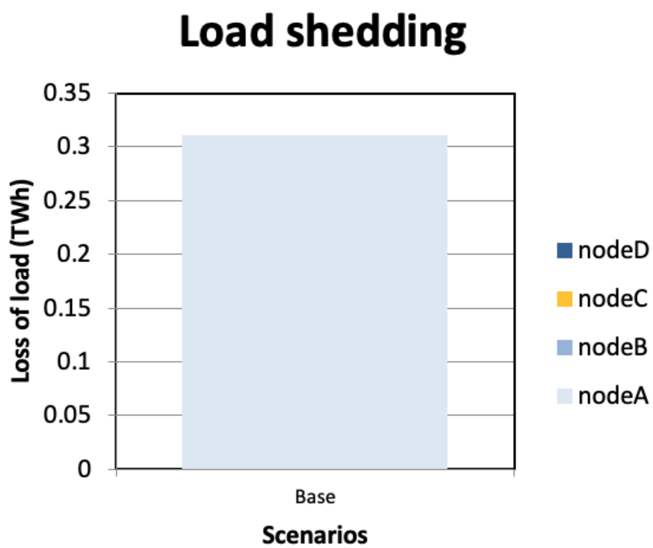


This figure shows us that peak demand is below dispatchable capacity (ST_coal, Engine_gas, CC_oil, ST_bio and Hydro_RES). Therefore, on the country level there should not be any issues with flexibility. The problem, may therefore arise from certain nodes or a single node.

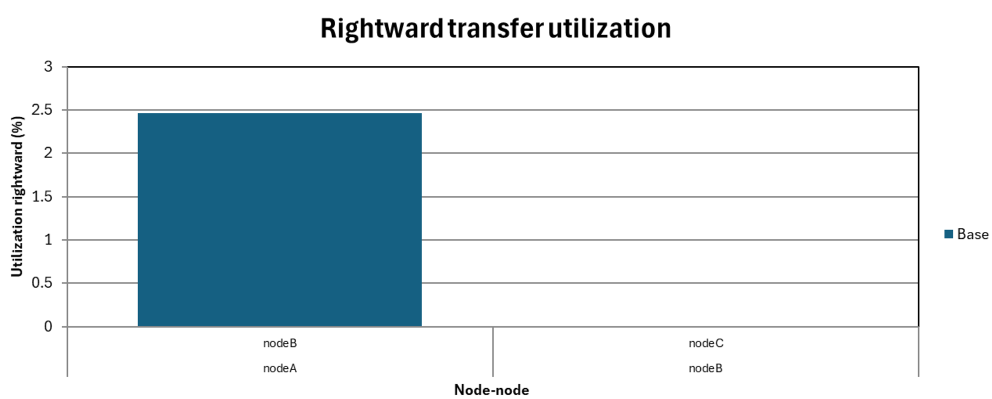
Digging deeper into flexibility

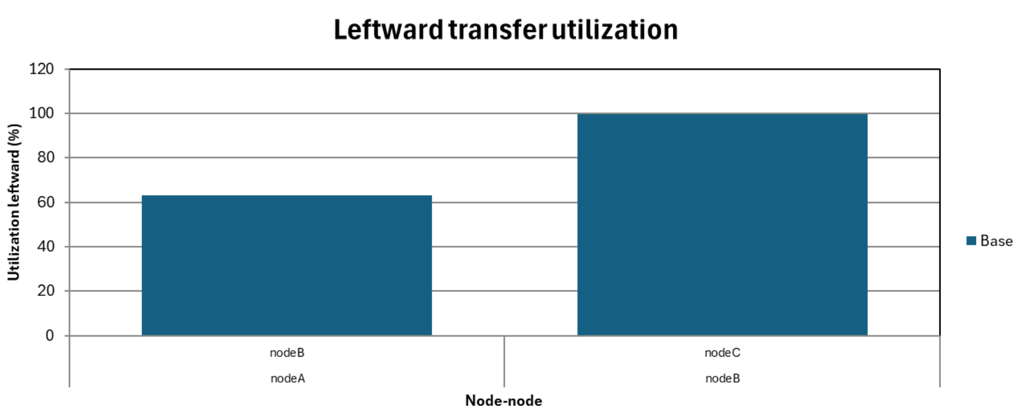
In this activity, we will try to further investigate where the origin of this loss of load is. To allow us to investigate whether this loss of load is originating from one of the nodes, open the "node_plot" sheet from the results file.

Within this "node_plot" sheet, we see a number of different plots which give us information on each of the nodes. The very first plot shows us that all of the load shedding occurs in nodeA, as shown below:



Next we'll look at the transfers between nodes, shown in the Figures below:





We see in these figures that nodeB transfers electricity to nodeA and nodeC transfers electricity to nodeB. And there is a marginal transfer from node A to node B.

The conclusion that we can get from these plots is that there is enough generation capacity, as shown in the previous activity, but this generation capacity is not where demand is and/or there is not enough transmission capacity.

This brings us to 3 possible solutions:

1. Invest in more transmission capacity.
2. Invest in more generation capacity.
3. Invest in storage

For this, the benefits and costs of each option should be explored before making a decision.

Assessing alternative scenarios

In this activity, we will adjust input data and run four additional scenarios to analyze the impact of each measure on system performance.

Scenario 1: Increased Transmission Capacity

Our analysis shows that nodeC is supplying electricity to nodeB at the maximum available capacity, creating a bottleneck. Increasing the transfer capacity into nodeB could also enable potential transfers to nodeA. The objective of this scenario is to allow investment in additional transmission capacity for the existing lines.

In the FlexTool package, there is a predefined scenario named demo1_invest_transCap. In the Sensitivity Definitions tab, you will see that this scenario has the "Invest" option activated in the Master Sheet section.

Scenario definitions master:	Sheet	co2_cost	loss_of_load_penalty	loss_of_reserves_penalty	lack_of_inertia_penalty	curtailment_penalty	lack_of_capacity_penalty	time_in_years	time_period_duration	reserve_duration	use_capacity_margin	use_online	use_ramps	use_non_synchronous	use_inertia_limit	mode_invest	mode_dispatch	print_duration	print_durationRamp
Invest	master															1			
deactivate_ramp	master												0						
demo1_invest_transCap	master															1			
demo1_invest_genCap	master															1			
demo1_invest_storages	master															1			
demo1_invest_all	master															1			
demo2_windGas	master															1			

The second activation to verify is in the sensitivity for the Nodenode sheet, where the **Max Invest (MW)** limits should be set to 1,000 MW for each connection. This high value effectively represents an unbounded limit, since the demand is comparable to the maximum transfer capacity.

Scenario definitions nodeNode:	Sheet	grid	node1	node2	cap.rightward (MW)	cap.leftward (MW)	invested capacity (MW)	max invest (MW)	loss	inv.cost/kW	lifetime	interest	annuity	HVDC
template_changeTransferCapacity	nodeNode	elec	nodeA	nodeB	1055									
demo1_invest_transCap	nodeNode	elec	nodeA	nodeB				1000						
demo1_invest_transCap	nodeNode	elec	nodeB	nodeC				1000						
demo1_invest_all	nodeNode	elec	nodeA	nodeB				1000						
demo1_invest_all	nodeNode	elec	nodeB	nodeC				1000						

Scenario 2: Increased Generation Capacity

As reviewed previously, we have a considerable loss of load, equivalent to around 3% of annual demand. To address this shortage, we will enable investment in the installation of new capacity for solar PV and wind power plants.

Similarly to the previous scenario, we will use the predefined case demo1_invest_genCap. Once again, the Invest mode should be activated in the Master sheet, as illustrated below.

Scenario definitions master:	Sheet	co2_cost	loss_of_load_penalty	loss_of_reserves_penalty	lack_of_inertia_penalty	curtailment_penalty	lack_of_capacity_penalty	time_in_years	time_period_duration	reserve_duration	use_capacity_margin	use_online	use_ramps	use_non_synchronous	use_inertia_limit	mode_invest	mode_dispatch	print_duration	print_durationRamp
Invest	master															1			
deactivate_ramp	master												0						
demo1_invest_transCap	master															1			
demo1_invest_genCap	master															1			
demo1_invest_storages	master															1			
demo1_invest_all	master															1			
demo2_windGas	master															1			

Next, we will set a new investment limit in the unitGroup sheet. In this case, we will apply more conservative figures, allowing 500 MW for solar and 350 MW for wind.

Add empty row

Scenario definitions unitGroup:	Sheet	unitGroup	max invest MW	min invest MW	max invest MWh	min invest MWh	print results
demo1_invest_genCap	unitGroup	Wind	350				
demo1_invest_genCap	unitGroup	PV	500				
demo1_invest_all	unitGroup	Wind	350				
demo1_invest_all	unitGroup	PV	500				

Scenario 3: Increased Storage Capacity

In this alternative scenario, we will enable additional investment in batteries to optimize the performance of the existing renewable energy capacity. As mentioned earlier, the invest mode must be activated for the scenario named **demo1_invest_storages**.

Add empty row

Scenario definitions master:	Sheet	co2_cost	loss_of_load_penalty	loss_of_reserves_penalty	lack_of_inertia_penalty	curtailment_penalty	lack_of_capacity_penalty	time_in_years	time_period_duration	reserve_duration	use_capacity_margin	use_online	use_ramps	use_non_synchronous	use_inertia_limit	mode_invest	mode_dispatch	print_duration	print_durationRamp
Invest	master															1			
deactivate_ramp	master												0						
demo1_invest_transCap	master															1			
demo1_invest_genCap	master															1			
demo1_invest_storages	master															1			
demo1_invest_all	master															1			
demo2_windGas	master															1			

In the unitGroup sheet, set both the *max invest (MW)* and *max invest (MWh)* to **150**, as the fixed MW/MWh ratio is set to 1 in the *demo1* file. The updated values should resemble the figure shown below.

Add empty row

Scenario definitions unitGroup:	Sheet	unitGroup	max invest MW	min invest MW	max invest MWh	min invest MWh	print results
demo1_invest_genCap	unitGroup	Wind	350				
demo1_invest_genCap	unitGroup	PV	500				
demo1_invest_all	unitGroup	Wind	350				
demo1_invest_all	unitGroup	PV	500				
demo1_invest_storages	unitGroup	Battery	150		150		
demo1_invest_all	unitGroup	Battery	150		150		

Likewise, we will define an initial existing storage capacity equal to the installed capacity of 0.01 in each node. This is configured in the units sheet, as shown in the figure below.

Add empty row

Can have only one input option (none, fuel, cf profile, inflow **or** input grid+node). Check carefully with input file if changing here.

Scenario definitions units:	Sheet	unitGroup	unittype	fuel	cf profile	inflow	input grid	input node	output grid	output node	capacity (MW)	invested capacity (MW)	max invest (MW)	storage (MWh)	invested storage (MWh)	max invest (MWh)	storage start	storage finish	reserve increase ratio
demo1_invest_storages	units		battery						elec	nodeA				0.01					
demo1_invest_storages	units		battery						elec	nodeB				0.01					
demo1_invest_storages	units		battery						elec	nodeC				0.01					
demo1_invest_all	units		battery						elec	nodeA				0.01					
demo1_invest_all	units		battery						elec	nodeB				0.01					
demo1_invest_all	units		battery						elec	nodeC				0.01					
	units																		

Scenario 4: Combined measures

The final scenario, named *demo1_invest_all*, integrates all the previously described strategies along with the corresponding changes in the relevant sheets, as outlined in earlier steps.

Running the scenarios

After updating the sensitivity definitions according to the previous instructions, proceed to the *sensitivity scenarios* tab. In this step, ensure that the **input file** is set to *demo1* and that the four different scenarios, plus the *Base* scenario for comparison, are activated. This should appear as shown in the figure below.

Active scenarios:		Inactive scenarios:
Base	<->	
	<->	Invest
	<->	
demo1_invest_transCap	<->	
demo1_invest_genCap	<->	
demo1_invest_storages	<->	
demo1_invest_all	<->	
	<->	
	<->	demo2_storages
	<->	demo2_PV
	<->	demo2_windGas
	<->	
	<->	
	<->	template_storageMW
	<->	template_storageFree
	<->	template_changeDemand
	<->	template_changeTransferCa
	<->	
	<->	
	<->	
	<->	

Comparing different investment options

Once we have the results file, let's check the first tab on Summary-D. Initially we can check the flexibility issues tables and compare the results of base scenario versus the different options as illustrated below.

	A	B	C	D	E	F
1	Update sheets window	demoModel-1	demoModel-1	demoModel-1	demoModel-1	demoModel-1
2		Base	demo1_invest_tr	demo1_invest_ge	demo1_invest_st	demo1_invest_all
22	General results	elec	elec	elec	elec	elec
23	VRE share (% of annual demand)	8.554	8.554	20.35	8.554	20.9
24	Loss of load (% of annual demand)	2.368	0	0.3663	1.444	0
25	-> ramp up constrained (% of annual demand)	0	0	0	0	0
26	Excess load (% of annual demand)	0	0	0	0	0
27	Insufficient reserves (% of reserve demand)	0	0	0	0	0
28	Insufficient inertia (% of inertia demand)					
29	Curtailment (% of VRE gen.)	-6.66E-06	-6.66E-06	2.53E-06	-6.66E-06	0.5985
30	-> ramp down constrained (% of VRE gen.)	0	3.07E-08	6.12E-09	0	1.95E-08
31	Peak load (MW)	2101.55	2101.55	2101.55	2101.55	2101.55
32	Peak net load (MW)	1946.3	1946.3	1919.74	1946.3	1916.79
33						
34	Flexibility issues	elec	elec	elec	elec	elec
35	Loss of load (max MW)	255.475	0	227.999	222.565	0
36	Excess load (max MW)	0	0	0	0	0
37	Reserve inadequacy (max MW)	0	0	0	0	0
38	Insufficient inertia (TWs/a)	0	0	0	0	0
39	Curtailment (max MW)	0.000137541	0.000137541	0.000887402	0.000137541	36.3083
40	Curtailment (TWh/a)	-7.48E-08	-7.48E-08	6.77E-08	-7.48E-08	0.0164392
41	Model leakage (TWh/a)	0	0	0	0	0
42	Capacity inadequacy (max MW)	0	0	0	0	0
43	Spill (TWh/a)	0	0	0	0	0

According to the results, transmission investments eliminated the loss of load, as did the combined strategy. Investments in generation and storage contributed positively to reducing the loss of load; however, it still remains. Additionally, in the invest all scenario, a small percentage of new curtailment appears.

In terms of costs, all scenarios proved to be less expensive than the base case. The invest all scenario provides the lowest total cost, at around USD 640 million. By investing in renewable energy, both operational costs and the loss of load penalty are reduced, more than offsetting the additional investment costs. Transmission investments also proved very cost-effective, significantly reducing the loss of load penalty and resulting in a total cost of approximately USD 680 million.

	A	B	C	D	E	F
1	Update sheets window	demoModel-1	demoModel-1	demoModel-1	demoModel-1	demoModel-1
2		Base	demo1_invest_tr	demo1_invest_ge	demo1_invest_st	demo1_invest_all
58	Costs	elec	elec	elec	elec	elec
59	Cost operations (M CUR)	609.876	574.333	491.268	618.36	447.003
60	Cost investments (M CUR)	0	4.86935	71.5061	1.40195	78.0548
61	Fixed annual costs (M CUR)	101.251	101.251	113.251	104.251	116.251
62	Cost loss of load (M CUR)	3110.96	0	481.27	1897.49	0
63	Cost excess load (M CUR)	0	0	0	0	0
64	Cost curtailment (M CUR)	-1.50E-06	-1.50E-06	1.35E-06	-1.50E-06	0.328784
65	Cost of insufficient reserves (M CUR)	0	0	0	0	0
66	Cost of insufficient inertia (M CUR)	0	0	0	0	0
67	Cost of insufficient capacity (M CUR)	0	0	0	0	0

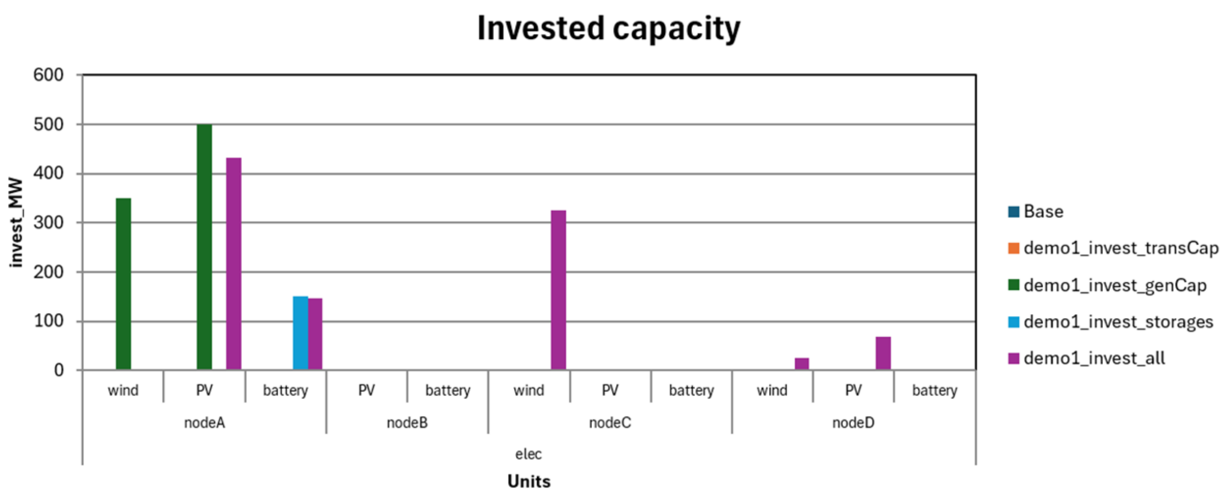
Going deeper into the investments performed in each scenario, we can examine the *Unit Type Capacity (MW)* and *Transfer Capacity (MW)* tables, as illustrated below. The additional investments stand out because they differ from the installed capacities in the base case.

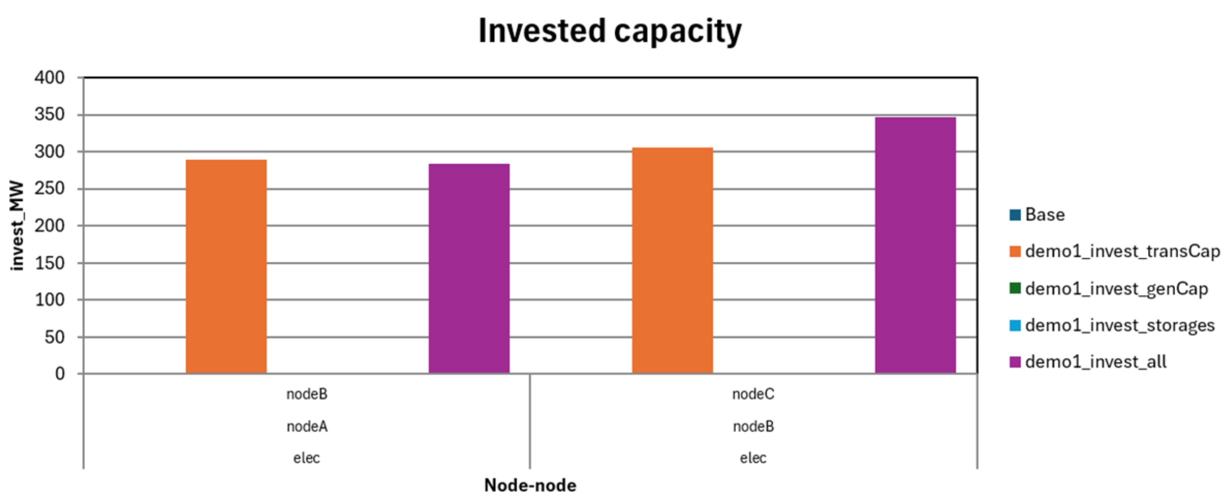
In the *transmission invest* scenario, additional transfer capacities of 290 MW were allocated between nodes A and B, and 305 MW between nodes B and C. In the *generation invest* scenario, the maximum caps were reached, with 350 MW of wind and 500 MW of PV added. Similarly, in the *storage invest* scenario, the full 150 MW of new battery capacity was utilized. Finally, in the *invest all* scenario, a combined portfolio of these different technologies was implemented.

	A	B	C	D	E	F
1	Update sheets window	demoModel-1	demoModel-1	demoModel-1	demoModel-1	demoModel-1
2		Base	demo1_invest_tr	demo1_invest_ge	demo1_invest_st	demo1_invest_all
80	Unit type	Capacity (MW)	Capacity (MW)	Capacity (MW)	Capacity (MW)	Capacity (MW)
81	ST_coal	1000	1000	1000	1000	1000
82	Engine_gas	300	300	300	300	300
83	CC_oil	620	620	620	620	620
84	ST_bio	45	45	45	45	45
85	Hydro_RES	150	150	150	150	150
86	Hydro_ROR	120	120	120	120	120
87	wind	150.02	150.02	500.02	150.02	500.02
88	PV	60	60	560	60	560
89	battery	0.04	0.04	0.04	150.04	150.04

1	Update sheets window	demoModel-1	demoModel-1	demoModel-1	demoModel-1	demoModel-1
2		Base	demo1_invest_tr	demo1_invest_ge	demo1_invest_st	demo1_invest_all
112	Transfer	Capacity (MW)	Capacity (MW)	Capacity (MW)	Capacity (MW)	Capacity (MW)
113	nodeA - nodeB	150	439.925	150	150	433.382
114	nodeB - nodeA	150	439.925	150	150	433.382
115	nodeB - nodeC	100	405.766	100	100	446.243
116	nodeC - nodeB	100	405.766	100	100	446.243

To explore the deployment of newly installed capacity per node, we can use the *units_invest_plot* sheet. The most significant investments occur in **node A**, where the loss of load was observed. Additional investment appears in **node C**, which serves as an option for transfers to other nodes, and finally, small investments are made in **node D**, which is an isolated node. Similarly, we can review the installed capacities in transmission by checking the *transfers_invest_plot* sheet. The reference figures are shown below.



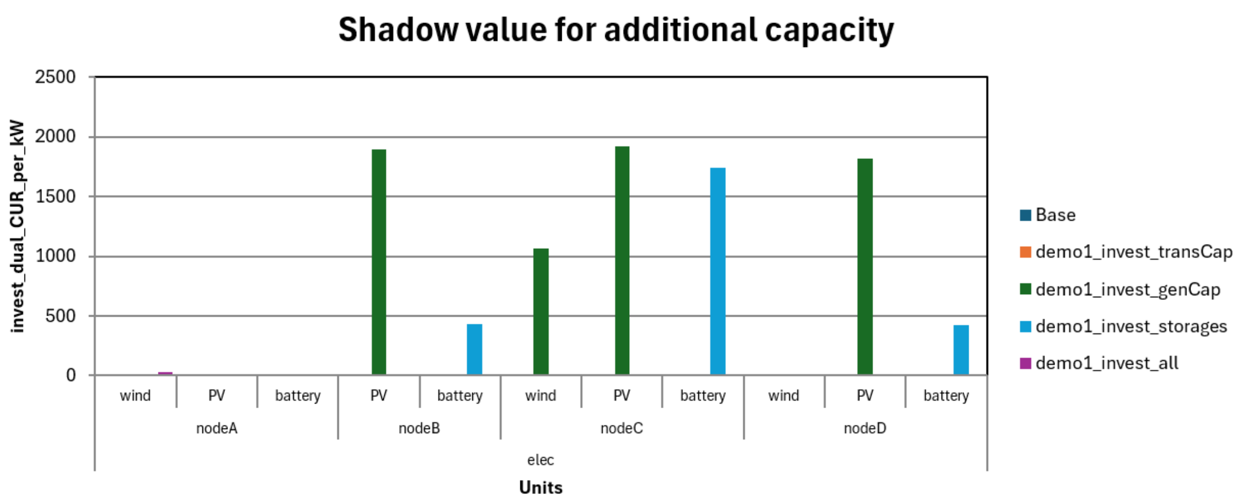


In the previous sheets, we can also observe the **shadow values** of additional investments. A shadow value is a model parameter that indicates whether further investment in a given technology would reduce the total system cost.

- If a technology shows a **positive shadow value**, this means that additional investment would **increase** total costs (i.e., it would not be profitable).

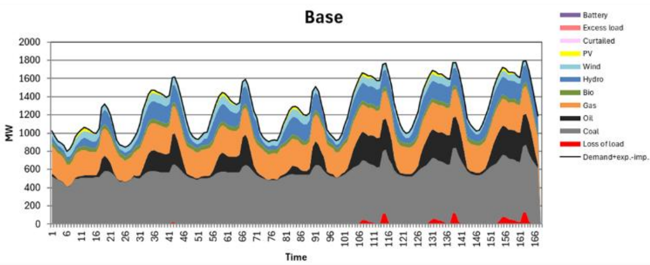
- Conversely, if a technology shows a **negative shadow value**, this means that further investment would **decrease** total costs, but some constraint (such as investment limits or technical restrictions) prevented the model from making that investment.

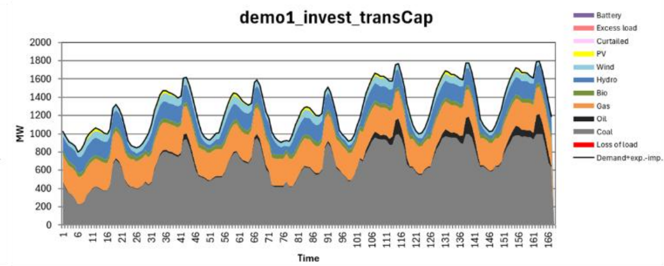
In our case, the results show that there are no remaining opportunities to reduce the total system cost through further investments.

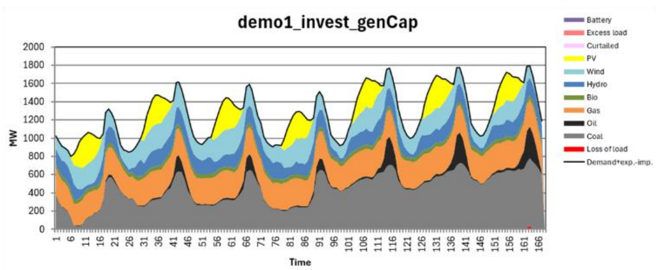


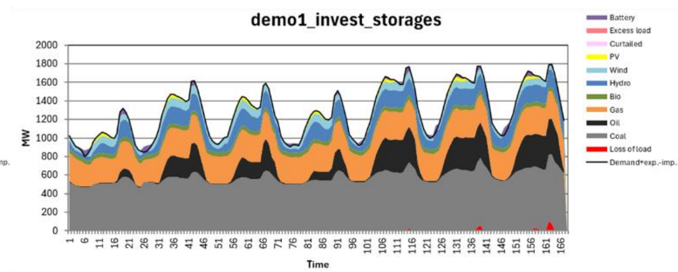
Now, in the *genUnitGroup_elec_plot* sheet, we can explore the weekly dispatch figures for each scenario, as shown below. Notice that the demand peak occurs after sunset. Nevertheless, PV remains a profitable investment since it helps reduce oil consumption. Without PV or wind, the model relies on oil capacity to cover the peak load when needed.

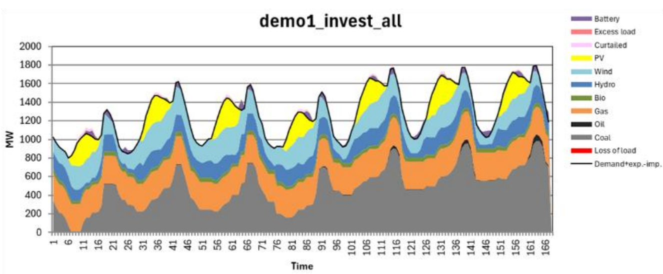
Note: You can change the week displayed by using the scroll bar at the top of the sheet.











Activity: Explore the other result sheets and evaluate what additional insights can be obtained for the flexibility assessment.