Main Findings from FRAMES Model Validation and Beta-Testing

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1. Updated FRAMES – IRENA FlexTool cross-validation results

IRENA’s FlexTool – simplified UC/ED model

Source: IRENA (https://www.irena.org/Energy-Transition/Planning/Flextool)

Version 3.0 (python based) is under development.

FRAMES – FlexTool Comparison. Technical

Feature	FRAMES	FlexTool (v2.0)
Optimization approach	MILP / LP	LP
Modelling language	AMPL (commercial, proprietary)	GNU MathProg (free, open source)
Solvers used	CPLEX (commercial, proprietary, faster)	CoinLP (CLP) (free, open source, slower)
User interface for input / output	Input: Excel Output: Excel	Input: Excel Output: Excel
Modes of operation	Dispatch + investment	Dispatch only / Dispatch + investment
Built-in capabilities for scenario analysis	No	Yes (scenario approach similar to MESSAGE, bunch start, parallel calculations)
Time representation	Only hourly	Flexible (use common sense)
Energy carriers representation	Limited (electricity, H2, heat?)	Flexible
Regional representation	Flexible ?	Flexible (use common sense)
Representation of technologies	Limited so far	Flexible (use common sense)
EV modelling	No	Yes, incl. flexible V2G operation

FRAMES – FlexTool Comparison. Dispatch / reserve representation

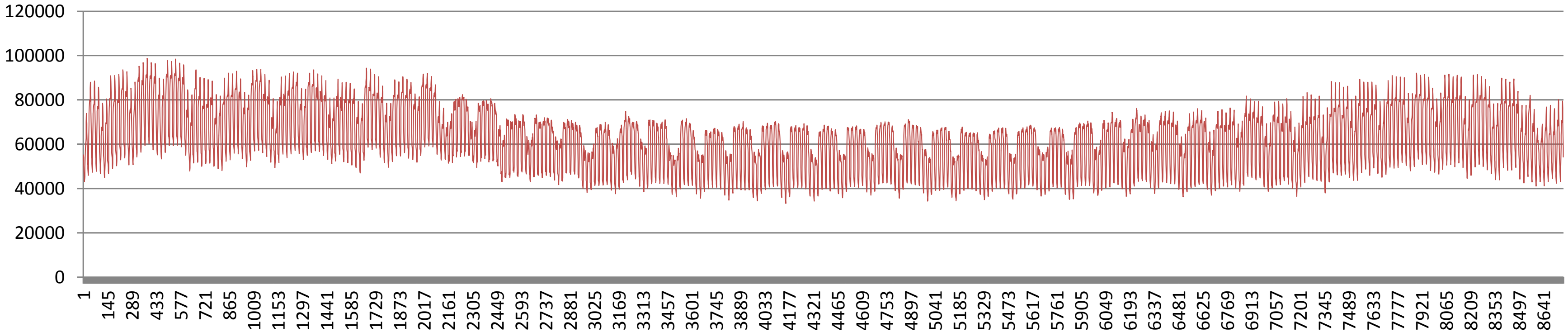
Feature	FRAMES	FlexTool (v2.0)
Dispatch capabilities		
	Start-up of units (integer)	Start-up of capacities (linear)
	Min generation constraint	Min / max generation constraints
	Min uptime/downtime	Min uptime/downtime
	Ramp up/down constraint	Ramp up/down constraint
	No system inertia constraint	System inertia constraint
Reserve modelling		
	Upward and downward reserve	Only upward reserves
	Two types of reserves	One type of reserves
	Only online units provide reserves	Only online capacity provide reserves
	VRE can provide reserves	VRE can’t provide reserves
	Reserve requirements calculated in the model based on % and hourly load	Reserve requirements should be pre-calculated based on % and hourly load

FRAMES – FlexTool Comparison. Hourly data

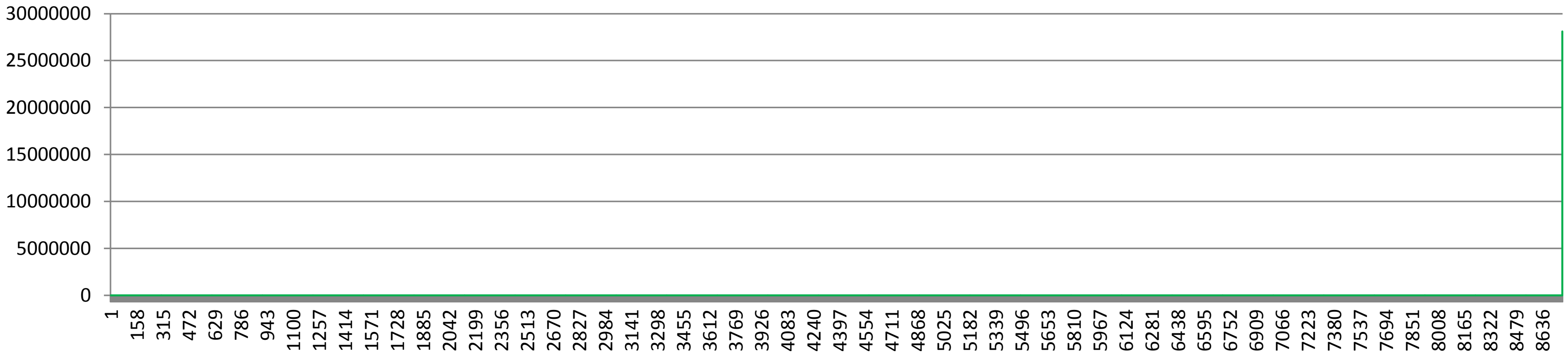
Feature	FRAMES	FlexTool (v2.0)	Assumption for validation run
Electricity demand representation	Hourly	Hourly	-
Hydrogen exogenous demand representation	Annual	Hourly (obligatory for all modelled energy carriers)	Mimicked (cost-free H2 storage + all demand at last hour of the year)
RES capacity factors	Hourly	Hourly	-
Efficiency time series for thermal generation	n/a	Hourly (optional) *(CHP modelling, GT modelling)*	Not used
Min / max / fix generation time series for thermal generation	n/a	Hourly (optional) *(maintenance, FOR)*	Not used
Inflows for hydro power plants	n/a	Hourly (obligatory)	No hydro

FRAMES – FlexTool Comparison. Demand representation

Total Annual Electricity Demand (Load)	**TWh**	**545.70**



Total Annual H2 Demand	**TWh**	**28.10**



FRAMES – FlexTool Comparison. Reserves / CO2 representation

In FRAMES we have 2 types of upward and downward reserves which calculated based on the total hourly load.

Only upward reserve requirement can be modelled in FlexTool.
Upward reserve requirements should be pre-calculated based on the specified percentage and an hourly load.

In FRAMES we have constraint on annual CO_2 emissions – 10 g CO_2/kWh

Unfortunately, FlexTool has no possibility to set CO_2 emissions limit, but it allows to include CO_2 costs.
So we put shadow price of CO_2 constraint from FRAMES as CO_2 cost in FlexTool - 153.64 \$/t CO_2

FRAMES – FlexTool Comparison. Technology inputs 1

unit type	fuel	cf profile	input grid	output grid	Existing capacity (MW)	invested capacity (MW)	max invest (MW)	Existing storage (MWh)	invested storage (MWh)	max invest (MWh)	storage start	storage finish
Large-scale NPP	nuc			elec	0.0		12000					
LWR-based SMR	nuc			elec	0.0		999999					
Gen IV cogeneration	nuc			elec	0.0		999999					
CCGT	gas			elec	0.0		999999					
CCGT + CCS	gas-ccs			elec	0.0		999999					
OCGT	gas			elec	0.0		999999					
CCGT Hydrogen			Hydrogen	elec	0.0		999999					
OCGT Hydrogen			Hydrogen	elec	0.0		999999					
Offshore Wind		wind_off		elec	0.0		999999					
Onshore Wind		wind_on		elec	0.0		999999					
Solar		PV		elec	0.0		999999					
Battery (2-hour)				elec	0.0		999999				0.65	0.65
Battery (4-hour)				elec	0.0		999999				0.65	0.65
Electrolyser			elec	Hydrogen	0.0		999999					
Steam-methane Reforming	smr-gas			Hydrogen	0.0		999999					
Steam-methane Reforming + CCS	smr-gas-ccs			Hydrogen	0.0		999999					
Demand response	demand			elec	7000.0							
Pumped hydro storage				elec	3000.0			26700			0.65	0.65

FRAMES – FlexTool Comparison. Technology inputs 2

unit type	efficiency	min load	eff at min load	ramp up (p.u. per min)	ramp down (p.u. per min)	inertia constant (MWs/MW)	max reserve	conversion eff	min uptime (h)	min downtime (h)	eff charge	self discharge loss
Large-scale NPP	1.00	0.25	1.00	0.01	0.01		1.00		24.0	8.0		
LWR-based SMR	1.00	0.25	1.00	0.01	0.01		1.00		24.0	8.0		
Gen IV cogeneration	1.00	0.25	1.00	0.01	0.01		1.00		24.0	8.0		
CCGT	0.57	0.20	0.57	0.01	0.04		1.00		6.0	4.0		
CCGT + CCS	0.50	0.20	0.50	0.01	0.04		1.00		6.0	4.0		
OCGT	0.37	0.20	0.37	0.02	0.04		1.00		1.0	1.0		
CCGT Hydrogen		0.20					1.00	0.56	6.0	4.0		
OCGT Hydrogen		0.20					1.00	0.39	1.0	1.0		
Offshore Wind	1.00			1.00	1.00		0.90		0.0	0.0		
Onshore Wind	1.00			1.00	1.00		0.90		0.0	0.0		
Solar	1.00			1.00	1.00		0.90		0.0	0.0		
Battery (2-hour)	1.00			1.00	1.00		1.00				0.90	0.00
Battery (4-hour)	1.00			1.00	1.00		1.00				0.90	0.00
Electrolyser								0.78				
Steam-methane Reforming	0.62											
Steam-methane Reforming + CCS	0.56											
Demand response	1.00											

We used the same technological inputs as in FRAMES for all generation and storage technologies, except for H2-to-power technologies where ramping constraint could not be set. Electrolysers electricity needs were converted to efficiency. S-M-R fuel costs were also onverted to efficiency.

FRAMES – FlexTool Comparison. Technology inputs – costs

unit type	Var O&M cost, $/MWh	fixed O&M cost, $/kW/year	Inv.cost, $/kW/year	Startup cost, $/MW
Large-scale NPP	1.5	111.1	321.3	500.00
LWR-based SMR	1.5	111.1	327.4	500.00
Gen IV cogeneration	1.5	111.1	357.2	500.00
CCGT	5.6	33.6	63.9	150.00
CCGT + CCS	9.9	35.3	142.6	150.00
OCGT	5.3	24.1	48.5	50.00
CCGT Hydrogen	1.3	21.6	39.4	84.00
OCGT Hydrogen	1.0	10.3	28.6	19.50
Offshore Wind	3.1	50.8	126.3	
Onshore Wind	3.1	61.1	82.0	
Solar	0.0	13.4	25.5	
Battery (2-hour)		4.0	13.3	
Battery (4-hour)		7.2	24.0	
Electrolyser	0.0	0.0	65.3	
Steam-methane Reforming	0.3	0.0	44.4	
Steam-methane Reforming + CCS	2.9	0.0	68.2	
Demand response	500.0			

fuel	fuel price, $/MWh	CO2 content, t/MWh
gas	20.1	0.20
nuclear	8.5	0.00
gas-ccs	20.1	0.02
smr-gas	20.1	0.17
smr-gas-ccs	20.1	0.02

Fuel costs are calculated based on the fuel price and efficiency of technology.

We used the same costs as in FRAMES for all generation and storage technologies. For H2 production and H2-to-power technologies we had to recalculate them since in Flextool all fixed costs should be expressed on a per MW of input basis (not output).

FRAMES – FlexTool Comparison. Optimization results 1

PARAMETER	Unit	FRAMES Value	FlexTool v2.0 Value	Note
PLATFORM INFORMATION				
Mathematical Optimization Method		**MILP**	**LP**	
Optimizer		**CPLEX**	**CLP**	
Run Time	[min]	**44.02**	**75**	FRAMES - NEOS server, FT – average PC
OBJECTIVE FUNCTION				
Total System Cost	Billion $	**37.611**	**37.35**	
Specific Cost of meeting Electricity Demand	[$/MWh$_e$]	**68.92**	**68.45**	
Specific Cost of meeting Electricity and Hydrogen Demand	[$/MWh$_e$+MWh$_{H2}$]	**65.55**	**65.09**	

FRAMES – FlexTool Comparison. Optimization results 2

PARAMETER	Unit	FRAMES Value	FlexTool v2.0 Value	Note
OPTIMIZED GENERATION CAPACITY		**139.755**	**143.352**	
Large-Scale Nuclear Power Plant (NPP) *(installed capacity 0 GW, potential capacity up to 17 GW)*	[GW]	**17**	**17**	
Light Water Reactor Technology-based Small Modular Reactor (SMR)	[GW]	**30.583**	**28.821**	
Advanced (Gen IV) Nuclear Reactor for Combined Heat and Power (CHPNPP)	[GW]	**0**	**0**	
Closed-Cycle Natural Gas Turbine (CCGT)	[GW]	**10.345**	**11.236**	
CCGT with Carbon Capture and Sequestration (CCGT+CCS)	[GW]	**6.944**	**7.372**	
Open-Cycle Natural Gas Turbine (OCGT)/Reciprocating Natural Gas Engine	[GW]	**0.839**	**7.160**	Because of CO2 constraint?
Closed-Cycle Hydrogen Turbine (CCHT)	[GW]	**0**	**0**	
Open-Cycle Hydrogen Turbine (OCHT)/Reciprocating Hydrogen engine	[GW]	**6.599**	**0**	
Distributed Solar (PV) *(installed 0 GW)*	[GW]	**0**	**0**	
Concentrating Solar *(installed 0 GW)*	[GW]	**41.633**	**43.925**	
Onshore Wind *(installed 0 GW)*	[GW]	**0**	**0**	
Offshore Wind *(installed 0 GW)*	[GW]	**25.812**	**27.837**	

FRAMES – FlexTool Comparison. Optimization results 3

PARAMETER	Unit	FRAMES Value	FlexTool v2.0 Value	Note
OPTIMUM STORAGE CAPACITY		**124.872**	**102.056**	
Reservoir (Dam) Storage (installed and potential 0 GW)	[GWh]	**0**	**0**	
Pumped Hydro Storage (installed and potential 26.7 GW)	[GWh]	**26.7**	**26.7**	
2-h Battery Storage	[GWh]	**37.503**	**0**	
4-h Battery Storage	[GWh]	**60.669**	**75.356**	
CURTAILMENT OF RENEWABLES				
Solar	[GWh]	**0**	**10.390**	0.03% of solar generation
Onshore Wind	[GWh]	**0**	**0**	
Offshore Wind	[GWh]	**0**	**0**	

Generation of PVs was partially curtailed since we don’t have curtailment penalty in the test case.

FRAMES – FlexTool Comparison. Optimization results 4

PARAMETER	Unit	FRAMES Value	FlexTool v2.0 Value	Note
ELECTRICITY SUPPLY		**600.66**	**571.61**	
Large-Scale Nuclear Power Plant (NPP)	[TWh]	**141.30**	**142.74**	
Light Water Reactor Technology-based Small Modular Reactor (SMR)	[TWh]	**265.47**	**247.48**	
Advanced (Gen IV) Nuclear Reactor for Combined Heat and Power (CHPNPP)	[TWh]	**0**	**0**	
Closed-Cycle Natural Gas Turbine (CCGT)	[TWh]	**12.75**	**14.00**	
CCGT with Carbon Capture and Sequestration (CCGT+CCS)	[TWh]	**20.36**	**22.33**	
Open-Cycle Natural Gas Turbine (OCGT)/Reciprocating Natural Gas Engine	[TWh]	**0.30**	**1.78**	
Closed-Cycle Hydrogen Turbine (CCHT)	[TWh]	**0**	**0**	
Open-Cycle Hydrogen Turbine (OCHT)/Reciprocating Hydrogen engine	[TWh]	**1.49**	**0**	
Solar	[TWh]	**36.84**	**38.87**	
Onshore Wind	[TWh]	**0**	**0**	
Offshore Wind	[TWh]	**99.58**	**107.38**	
Reservoir (Dam) Storage	[TWh]	**0**	**0**	
Pumped Hydro Storage	[TWh]	**2.41**	**-0.85**	Should be shown as net consumers to avoid double counting
2-h Battery Storage	[TWh]	**6.70**	**0**	
4-h Battery Storage	[TWh]	**13.46**	**-2.12**	
OTHER SYSTEM ELEMENTS				
DSM (limit 7 GW)	[TWh]	**0.32**	**0.38**	
Not Served Energy	[TWh]	**0**	**0**	

FRAMES – FlexTool Comparison. Optimization results 5

PARAMETER	Unit	FRAMES Value	FlexTool v2.0 Value	Note
HYDROGEN SUPPLY				
Total H_2 supply	[TWh_H_2]	**32.625**	**28.100**	
H_2 Supplied by Electrolysis Systems	[TWh_H_2]	**23.391**	**19.380**	
H_2 Supplied by High Temperature Process Systems	[TWh_H_2]	**0**	**0**	
H_2 Supplied by S-M-R Systems w/o CCS	[TWh_H_2]	**0**	**0**	
H_2 Supplied by S-M-R Systems with CCS	[TWh_H_2]	**9.234**	**8.719**	
HYDROGEN UTILIZATION				
H_2 used for generation units	[TWh_H_2]	**4.525**	**0**	
H_2 sold to exogenous use	[TWh_H_2]	**28.1**	**28.1**	

FRAMES – FlexTool Comparison. Optimization results 6

PARAMETER	Unit	FRAMES Value	FlexTool v2.0 Value	Note
EMISSIONS				
Total CO_2 emitted	[Million ton]	**5.738**	**7.091**	No CO2 constraint
CO_2 emitted by the thermal generation units	[Million ton]	**5.506**		
CO_2 emitted by the S-M-R Systems	[Million ton]	**0**		
CO_2 emitted by the S-M-R Systems with CCS	[Million ton]	**0.232**		
Specific CO_2 Emission for meeting Electricity and Hydrogen	[$/MWh_e+MWh_{H2}$]	**10**	**12.4**	
Specific CO_2 Emission for meeting Electricity Demand	[$/MWh_e$]	**10.09**		
Specific CO_2 Emission for meeting Hydrogen Demand	[$/MWh_{H2}$]	**8.25**		
CO_2 price	[$/ton]	**153.64**	**153.64**	Set to mimic CO2 constraint

CO2 emissions are 25% higher in FlexTool compared with FRAMES

FRAMES – FlexTool Comparison. Optimization results 7 – updated

PARAMETER	Unit	FRAMES Value	FlexTool v2.0 Value	Note
BREAK-DOWN OF OBJECTIVE FUNCTION	**[Billion $]**	**37.60**	**38.44**	
Fixed capital cost thermal units	[Billion $]	**17.45**	**17.02**	
Fixed Operational cost thermal units:	[Billion $]	**6.07**	**5.90**	
Variable and startup cost of thermal units	[Billion $]	**5.67**	**5.74**	
Total cost of energy not served	[Billion $]	**0**	**0**	
Total cost of reserved not served	[Billion $]	**0**	**0**	
Total cost of DSM	[Billion $]	**0.16**	**0.19**	
Capital cost of storage	[Billion $]	**0.8**	**0.45**	
Fixed capital cost solar	[Billion $]	**1.62**	**1.71**	
Fixed capital cost wind - onshore	[Billion $]	**0**	**0**	
Fixed capital cost wind - offshore	[Billion $]	**4.57**	**4.93**	
Variable cost of solar and wind	[Billion $]	**0.31**	**0.52**	
Capital cost electrolysers	[Billion $]	**0.52**	**0.48**	
Capital cost S-M-R Systems with CCS	[Billion $]	**0.12**	**0.07**	
Variable costs of H_2 production S-M-R Systems with CCS	[Billion $]	**0.31**	**0.34**	
Revenue from H_2 sold (negative)	[Billion $]	**0**	**0**	
Cost of CO_2 emitted by thermal units	[Billion $]	**0**	**1.05**	
Cost of CO_2 for H_2 production S-M-R Systems with CCS	[Billion $]	**0**	**0.04**	
TOTAL COSTS w/o CO2 costs	[Billion $]	**37.60**	**37.35**	≈ 0.7%

Conclusions / Recommendations – MAJOR

1) FRAMES – FlexTool cross-validation went well as we have very similar optimization results given differences between the models. The only major difference is the use of H2 for power generation.
2) UC/ED models (even with an “investment mode”) should not be considered as a substitute for the long-term dynamic capacity expansion models
3) It should be possible to run the model in non-integer mode. Otherwise, for large systems, the computation time will be very long. Not everyone has access to commercial solvers – FIXED
4) Improve flexibility of representation of energy carriers, regions, technologies (hydro, CHP, etc.). In its current state, the scope of FRAMES application is limited.
5) Possibility to model EVs, including flexible V2G operation
6) H2 storage with corresponding costs and losses should be modelled. Exogenous H2 demand should be presented at least in monthly/weekly domain.
7) System inertia limit should be considered.

2. FRAMES Beta-testing activities and results

Plan of beta-testing activities

The Challenge:

An initial idea of case study for a Russian region proved unfeasible without considering CHPs, even in southern regions of country.

A dual-path beta-test

Track A: Core Capabilities

Objective: Stress-test the model's fundamental mechanics.

Method: Running the model through various hypothetical research scenarios to ensure mathematical and economic logic is sound

Track B: “Real” System Application

Objective: Test the model on a small, “close to real-world” system

Method: Modelling the decarbonization of a hypothetical small island (inspired by the IAEA's Antigua ESST case study)

Track A – List of Hypothetical Research Cases

Case	Description 1	Description 2
1	500 hours period in the middle of the year	CO2 limit = 10 kg/MWh
2	Full leap year	CO2 limit = 10 kg/MWh
3	500 hours period in the middle of the year	CO2 limit - none, CO2pr=10,H2pr=5
4	500 hours period in the middle of the year	no CO2 limit, CO2price=0, H2price=0
5	500 hours period in the middle of the year	no CO2 limit, CO2price=0, H2price=1
6	500 hours period in the middle of the year	no CO2 limit, CO2price=10, H2price=1
7	500 hours period in the middle of the year	no CO2 limit, CO2price=100, H2price=5
8	500 hours period in the middle of the year	no CO2 limit, CO2price=300, H2price=0
9	Case 1 + only 4-hour storages are in optimization	CO2 limit = 10 kg/MWh
10	Case 1 + Hydro RoR and Dam added	CO2 limit = 10 kg/MWh

All hypothetical cases were based on the *FRAMES_VerB_Input_Assumption_UserAid_R1.xlsx* provided by IAEA

Track B – List of Small Island System Cases

№	Electricity demand	Candidate technologies	Carbon intensity of electricity generation, kg CO_2/MWh	CO_2 price, \$/tCO_2
0	Base	Only capacities obtained from ESST simulation	-	-
1	Base	oil, solar, wind	-	-
2	Base	oil, solar, wind, batteries,	-	-
3	Base	oil, solar, wind, batteries, H2 (prod+storage+el.generation)	-	-
4	Base	oil, solar, wind, batteries	50	-
5	Base	oil, solar, wind, batteries, H2 (prod+storage+el.generation)	50	-
6	Base	oil, solar, wind, batteries	10	-
7	Base	oil, solar, wind, batteries, H2 (prod+storage+el.generation)	10	-
8	Base + EV	oil, solar, wind, batteries, H2 (prod+storage+el.generation)	50	-
9	Base + EV	oil, solar, wind, batteries, H2 (prod+storage+el.generation)	10	-
10	Base	oil, solar, wind, batteries, H2 (prod+storage+el.generation)	-	50
11	Base	oil, solar, wind, batteries, H2 (prod+storage+el.generation)	-	100
12	Base	oil, solar, wind, batteries, H2 (prod+storage+el.generation)	-	200

Starting with the Case 4, we were not able to get the results in MILP formulation in reasonable time (8 hours on NEOS server).

So we had to switch to “relaxed” optimization.

The optimization results were satisfactory after that.

Beta-Testing – Major Issues Found (1)

Issue 1 – The inability to model the operation of CHP plants.

Possible temporary fix: incorporate into the model the ability to specify hourly minimum generation levels for certain thermal power plants

Issue 2 – CO2 emissions constraint doesn't work properly when modelling part of the year.

In the equation limiting CO2 emissions, the maximum specific CO2 emission factor (input parameter) is multiplied by the **annual** demand for electricity and hydrogen:

*(<= MAX_CO2[r] * (LOAD_EL_TWH[r] + LOAD_H2_TWH[r]) * 1E6);*

Possible fix: LOAD_EL_TWH[r] + LOAD_H2_TWH[r] should be corrected by the fraction of the demand in part of the year in consideration.

Beta-Testing – Major Issues Found (2)

Issue 3 – Possible wrong representation of the storages.

Model can invest in “excluded” BESS/PH technologies. Additional BESS/PH will not appear if NO storage technologies at all were selected for inclusion into the model.

‘OPTION_St’ parameter used only in the objective function and electrical load balance (P_LOAD_bal). That means that “excluded” storage options can still contribute to all of the storage constraints, with no costs actually.

Possible fix: Maximum storage capacity should be set to 0 if ‘OPTION_St’ = 0.

Set-up file

param:	OPTION_St_L		Eta_St_L
1	0	1.00	0.00011
2	0	0.75	0.11236
3	1	0.90	0.50000
4	0	0.90	0.25000
5	0	0.90	0.10000

;

Results file

```
===============================================
        Electricity Storage Summary
===============================================
```

Region	Technology	Installed Capacity [GWh]	Electricity Supply [MWh]
1	Dam Hydro	0.000	0.00000000e+00
1	Pumped Hydro	26.700	3.73230625e+06
1	2-hour BESS	10.856	3.20112653e+06
1	4-hour BESS	26.090	9.60790516e+06
1	12-hour BESS	0.000	0.00000000e+00

Beta-Testing – Major Issues Found (3)

Issue 4 – Constraints on the maximum output (capacity) of RES power plants.

During modelling of a small island power system, we found that the RES development may exceed the available potential. So it’s really needed to have a possibility to set a constraint on maximum generation or capacity of certain types of RES power plants.

Issue 5 – User-proof measures.

To minimize the risk of incorrect data entry, it is advised to implement validation rules that restrict input to predefined ranges or allow selection through dropdown lists. Additionally, some cells can be locked to prevent accidental changes.

It is also necessary to verify that the load profile is normalized. Alternatively, it would be better to add a possibility to automatically re-normalize the load profile when the model is being generated.

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Thank you for your attention!