DDCA Project Final Quarterly Report

September 29, 2019

Contents

1 Introduction

The objective of this report is to showcase the final transition scenario results from the Demand-Driven CYCAMORE Archetypes project (NEUP-FY16-10512). The motivation for the project and description of the implementation of `d3ploy` (demand driven capability in CYCLUS) is previously described in the UIUC-ARFC-2019-03 report. This report seeks to further the work by demonstrating the use of `d3ploy` to set up EG01-23, EG01-24, EG01-29, and EG01-30 transition scenarios with constant and linearly increasing power demand curves. Table 1 provides a description of these fuel cycles: EG23, EG24, EG29, and EG30.

Table 1: Descriptions of the current and other high performing nuclear fuel cycle evaluation groups described in the evaluation and screening study [1].

Fuel Cycle	Open or Closed	Fuel Type	Reactor Type
EG01 (current)	Open	Enriched-U	Thermal critical reactors
EG23	Closed	Recycle of U/Pu with natural-U fuel	Fast critical reactors
EG24	Closed	Recycle of U/TRU with natural-U fuel	Fast critical reactors
EG29	Closed	Recycle of U/Pu with natural-U fuel	Fast critical reactors and thermal critical reactors
EG30	Closed	Recycle of U/TRU with natural-U fuel	Fast critical reactors and thermal critical reactors

1.1 Breakdown

Each section in this report demonstrates the use of `d3ploy` to set up a transition scenario. We will be looking at constant power demand transition scenarios for EG01-23 and EG01-29, and linearly increasing power demand transition scenarios for EG01-24 and EG01-30. All the results from this report is accessible a github repository [2].

2 Eg01-Eg23

Figure 1 shows the facility and mass flow of transition scenario Eg01-Eg23 in CYCLUS.

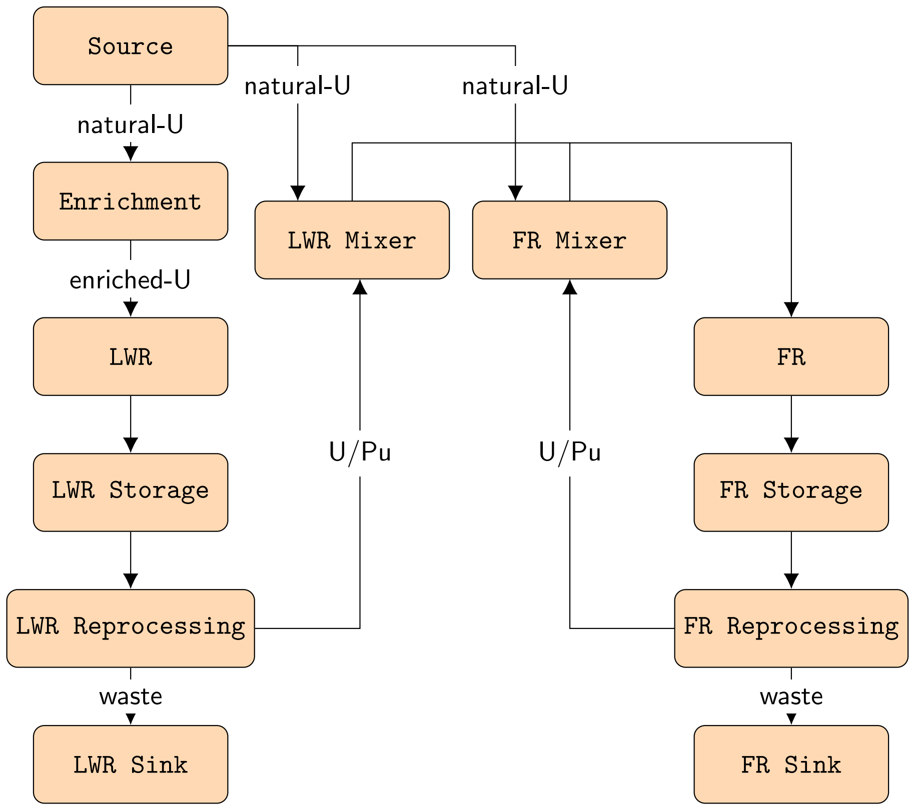


Figure 1: Diagram with facilities and mass flow of the scenario EG01-EG23.

2.1 Flat Power Demand: Power

This section presents plots of power for all the prediction methods. The power demand is 60000 MW throughout the whole simulation. Table 2 shows the input parameters. Figures 2, 3, and 4 display the power demand and corresponding supply from the Non-optimizing (NO), Deterministic-optimizing (DO), and Stochastic-optimizing methods (SO), respectively. The plots only show the power demand and supply during the transition period as undersupply mostly occurs during the transition period. Undersupply of power occur during two main time periods: initial demand for the commodity and during the transition period. Undersupply time steps occurring at the beginning of the simulation is expected since without time series data at the beginning of the simulation, `d3ploy` takes a few time steps to collect time series data about power demand to begin predicting and starting deployment of reactor and supporting fuel cycle facilities. Table 3 records the number of steps with undersupply, the cumulative undersupply, and the cumulative oversupply for each prediction method simulation. Cumulative undersupply and cumulative oversupply represent the summation of the difference between the power supplied and the power demanded for all the time steps in the simulation. This magnitude could be best understood as energy. The cumulative undersupply represents the energy not provided during the time steps in which the supply did not meet the demand. Likewise, the oversupply is the excess of energy produced. In table 3 we see that the smallest cumulative under supply and smallest amount of undersupply time steps are for poly and fft prediction methods.

Table 2: EG01-EG23 input file values.

Parameter	Value
Demand equation	6e4
Installed Capacity	1
Buffer	0
Forward Steps	1
Backward Steps	2

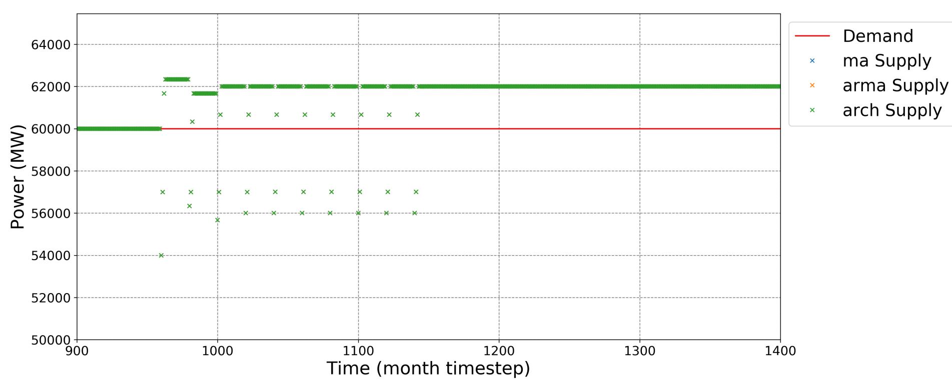


Figure 2: Constant power demand of 60GW and power supply obtained with the NO algorithms.

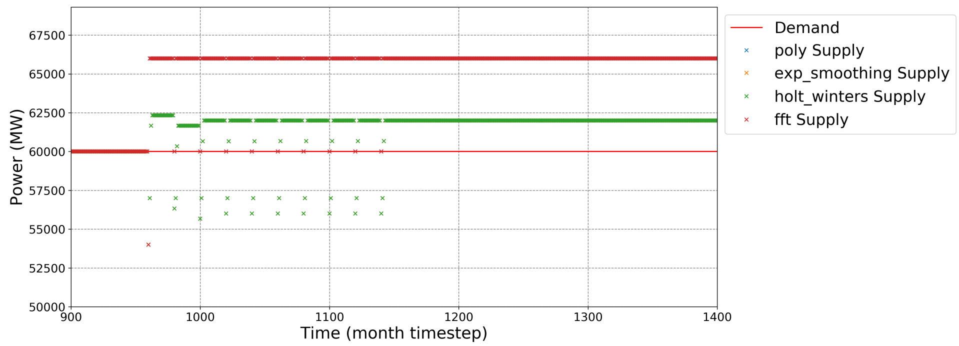


Figure 3: Constant power demand of 60GW and power supply obtained with the DO algorithms.

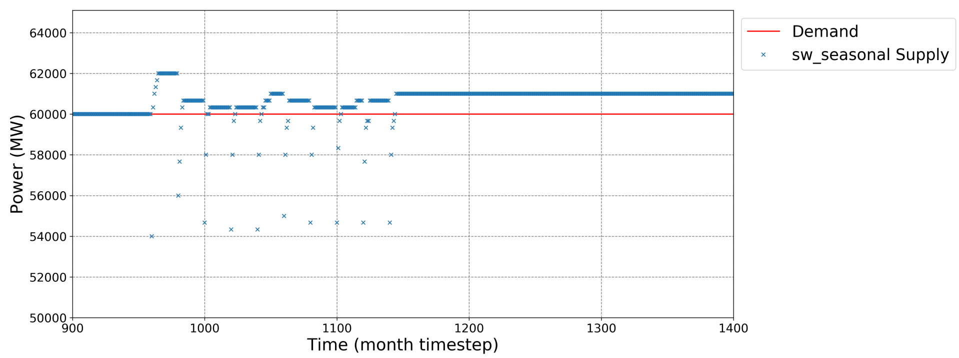


Figure 4: Constant power demand of 60GW and power supply obtained with the SO algorithms.

Table 3: Undersupply and oversupply of Power for the different prediction algorithms used to calculate EG01-EG23.

Algorithm	Undersupplied Timesteps	Cumulative Undersupply [GW.mo]	Cumulative Oversupply [GW.mo]
MA	26	306.0	907.8
ARMA	26	306.0	907.8
ARCH	26	306.0	907.8
POLY	6	235.0	2820.5
EXP_SMOOTHING	27	366.0	907.8
HOLT-WINTERS	27	366.0	907.8
FFT	8	307.0	2820.5
SW_SEASONAL	36	308.0	398.1

2.2 Sensitivity Analysis: Power Buffer

This section presents a sensitivity analysis for different values of the power buffer. Figure 5 shows a comparison of the cumulative undersupply for different buffer sizes for different prediction methods. The cumulative undersupply, remains constant for some of the methods and decreases with the increase of the buffer for others. Figure 6 displays the power demand and supply for different values of the buffer using poly. For this case, the undersupply remains constant. Figure 6 helps to understand the observed behavior. During at the transition we can see that even for the buffer with size 0 MW there is no undersupply. Thus, increasing the buffer will not decrease an undersupply that is already zero.

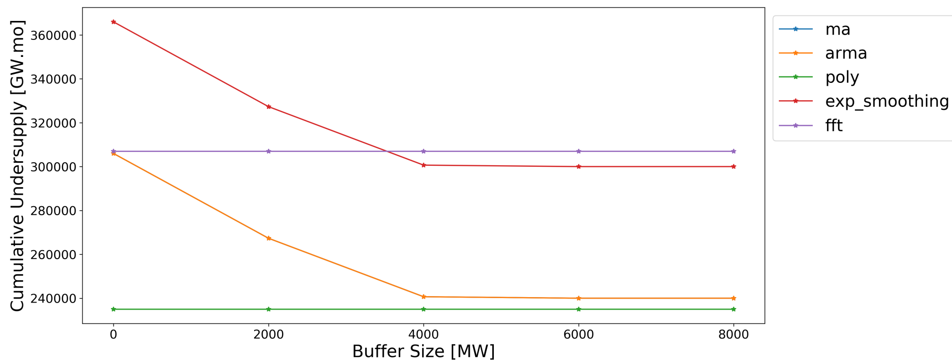


Figure 5: Sensitivity analysis for different buffer sizes for different prediction algorithms.

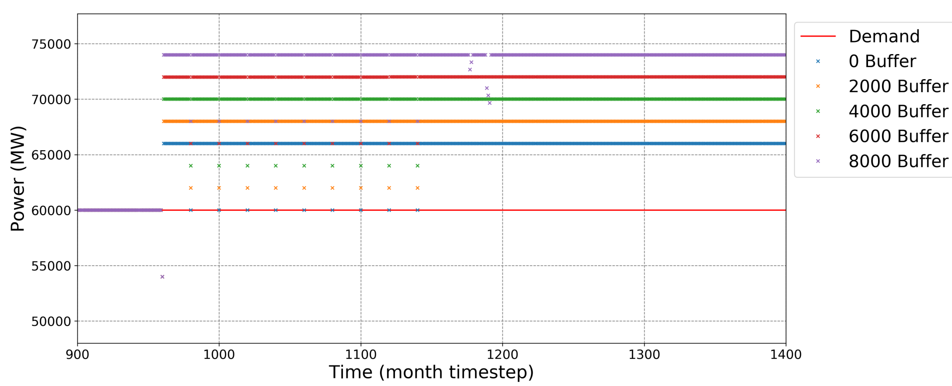


Figure 6: Power supply for different buffer sizes using poly.

2.3 Sensitivity Analysis: Forward Steps

This section presents a sensitivity analysis for different number of forward steps. Figure 7 shows a plot of the cumulative undersupply varying number of forward steps using the poly prediction method. Slightly increasing the number of forward steps decreases the undersupply. Increasing the number of forward steps too much has a negative impact on the results. Figures 8 displays the plots for power supply for different number of forward steps. For 4 and 5 forward steps, the undersupply increases. Increasing the number of forward steps enlarges the production of power, more reactors are deployed and consequently, the new reactors require more fuel. As they require more fuel, the available fuel will not be enough, and the scenario will fail. Figure 9 helps to understand this behavior. This figure shows that the demand of fuel for the FRs is larger than the supply of the same commodity. The forward steps capability should be used only with small number of forward steps to avoid this undersupply from occurring.

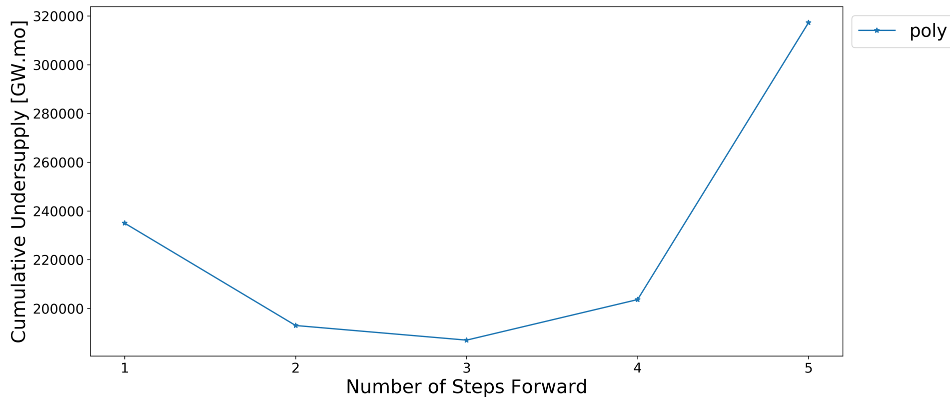


Figure 7: Cumulative undersupply varying the number of forward steps using the poly prediction method.

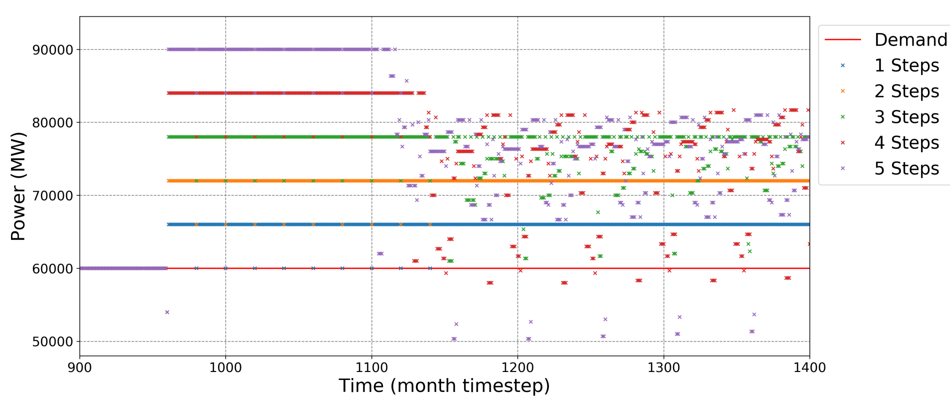


Figure 8: Power supply varying the number of forward steps using the poly prediction method.

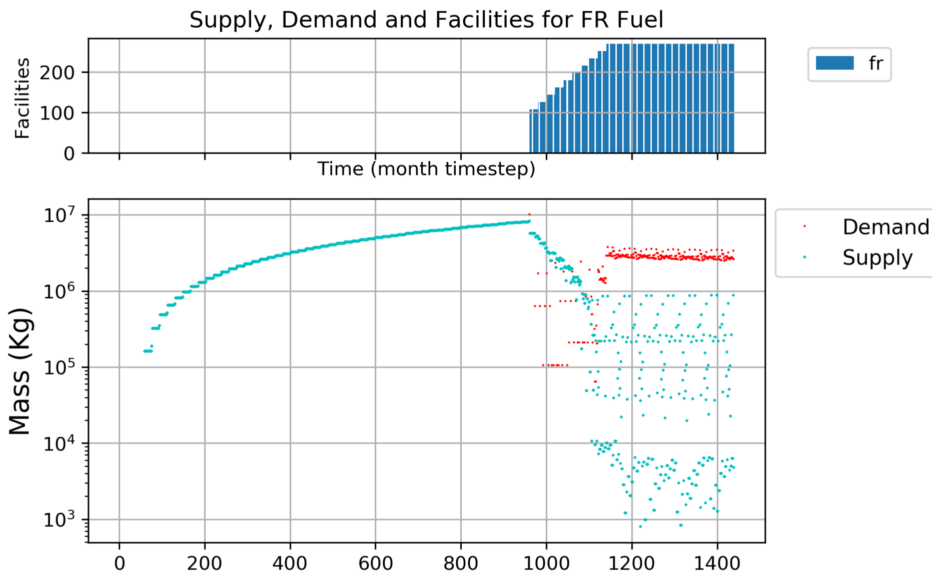


Figure 9: Power supply for 5 forward steps using the poly prediction method.

2.4 Flat Power Demand: Meaningful Commodities

Using the best prediction method, poly, this section presents plots for the supply and demand of the most meaningful commodities in the transition scenario. Table 4 summarizes which commodity each figure in this section corresponds to. Table 5 presents the number of steps of undersupply, cumulative undersupply, and cumulative oversupply for each commodity.

Table 4: Commodity names used in the simulation of EG01-EG23.

Commodity	Figure
Power	10
Natural-U	11a
Enriched-U	11b
FR fuel	12
Reprocessed Pu from spent fuel of LWRs	13a
Reprocessed Pu from spent fuel of FRs	13b

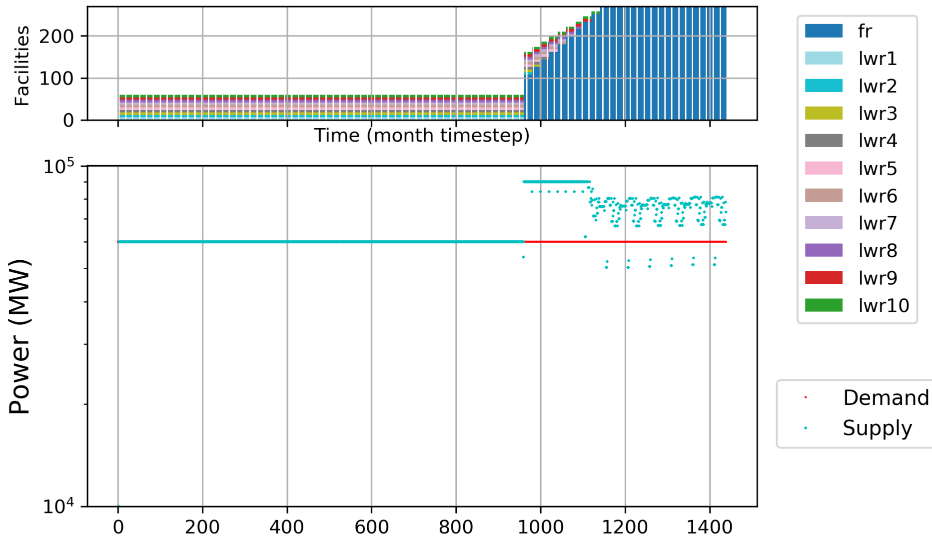
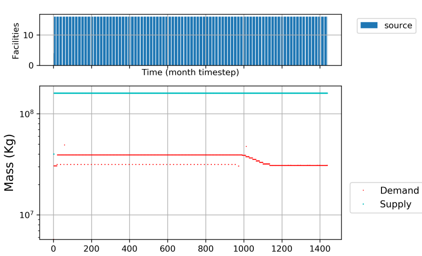
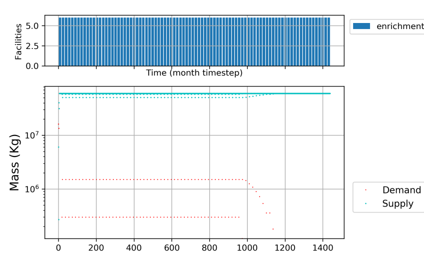


Figure 10: Demand and supply of Power and number of reactors deployed.



(a) Natural-U.



(b) Enriched-U.

Figure 11: Demand and supply of different commodities and number of facilities that produce them.

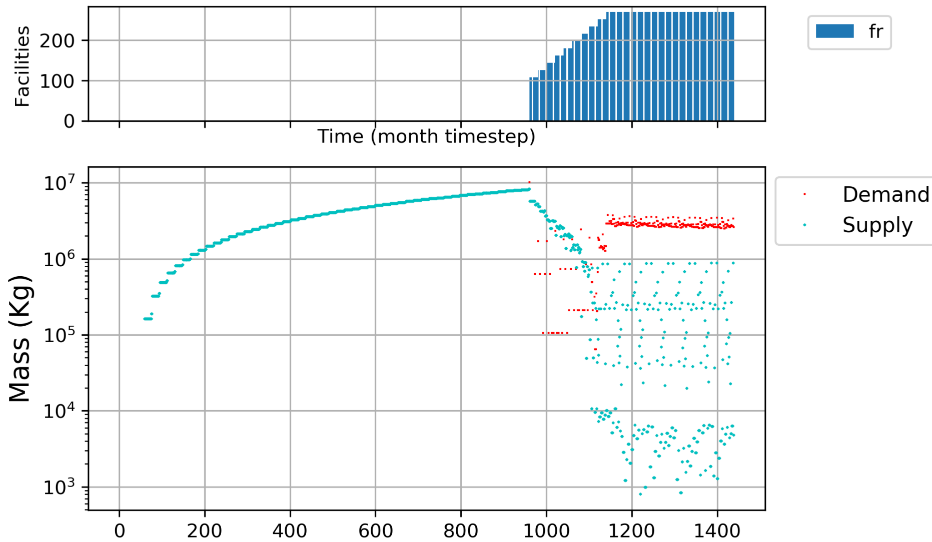
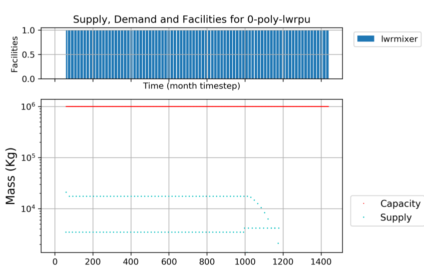
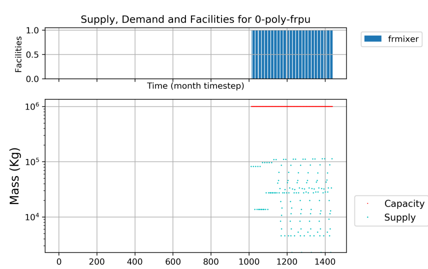


Figure 12: Demand and supply of FR fuel and number of FR reactors.



(a) Reprocessed Pu from spent fuel of LWRs.



(b) Reprocessed Pu from spent fuel of FRs.

Figure 13: Demand and supply of different commodities and number of facilities supplied with them.

Table 5: Undersupply and oversupply of different commodities using poly to calculate EG01-EG23.

Commodity	Undersupplied Timesteps	Cumulative Undersupply [10^3Kg]	Cumulative Oversupply [10^6Kg]
Natural-U	2	4713	35648
Enriched-U	4	$48.5 \cdot 10^3$	42259
Reprocessed Pu from spent fuel of LWRs	1	1.7	-
Reprocessed Pu from spent fuel of FRs	1	27.4	-

3 Eg01-Eg24

Figure 14 shows the facility and mass flow of transition scenario Eg01-Eg24 in CYCLUS.

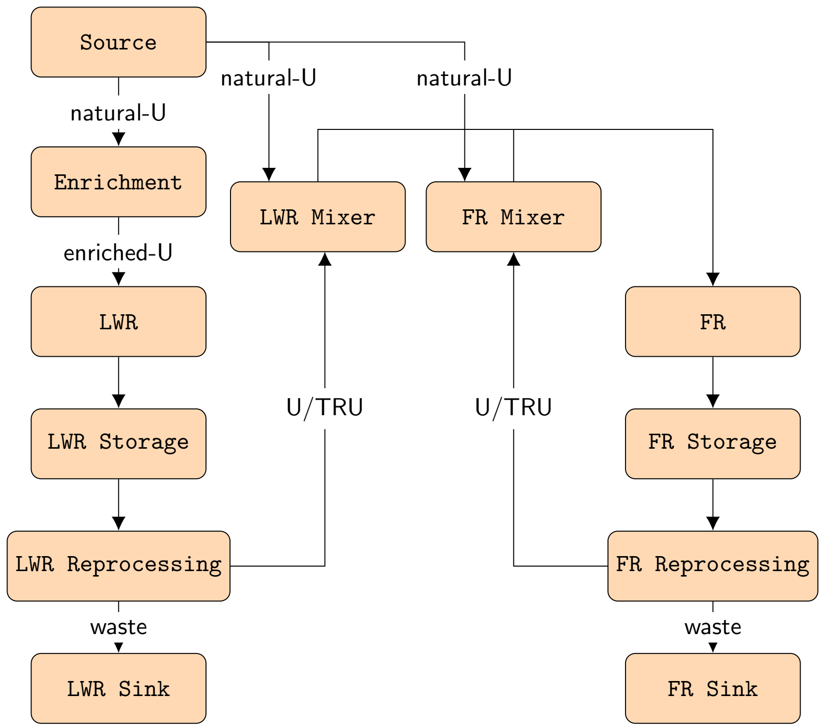


Figure 14: Diagram with facilities and mass flow of the scenario EG01-EG24.

3.1 Linearly increasing Power Demand: Power

This section presents plots of power for all the prediction methods. The power demand increases linearly with the expression $60000 + 250t/12MW$. Table 6 shows the input parameters. Figures 15, 16, and 17 display the power demand and corresponding supply for the Non-optimizing (NO), Deterministic-optimizing (DO), and Stochastic-optimizing methods (SO), respectively. The plots only show the power demand and supply during the transition period. Undersupply of power occur during two main time periods: initial demand for the commodity and during the transition period. Undersupply time steps occurring at the beginning of the simulation is expected since without time series data at the beginning of the simulation, `d3ploy` takes a few time steps to collect time series data about power demand to begin predicting and starting deployment of reactor and supporting fuel cycle facilities. Table 7 records the number of steps of undersupply, the cumulative undersupply, and the cumulative oversupply. The smallest cumulative undersupply and smallest amount of undersupply time steps are for the fft prediction method.

Table 6: EG01-EG24 input file values.

Parameter	Input
Demand equation [MW]	$60000 + 250t/12MW$
Deployment Driving Method	Installed Capacity
Power Buffer [MW]	0
Forward Steps	1
Backward Steps	2

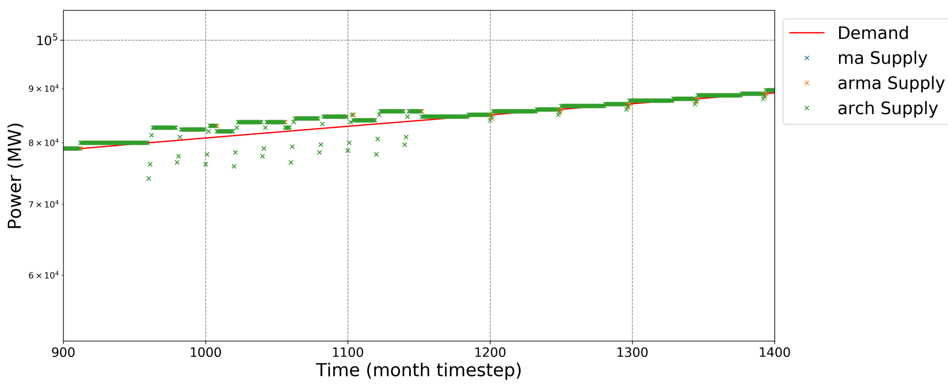


Figure 15: Linearly increasing power demand ($60000 + 250t/12MW$) and power supply obtained with the NO algorithms.

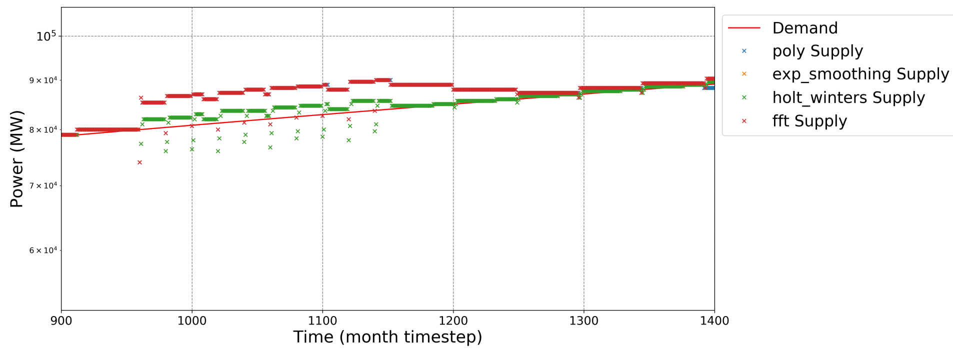


Figure 16: Linearly increasing power demand ($60000 + 250t/12MW$) and power supply obtained with the DO algorithms.

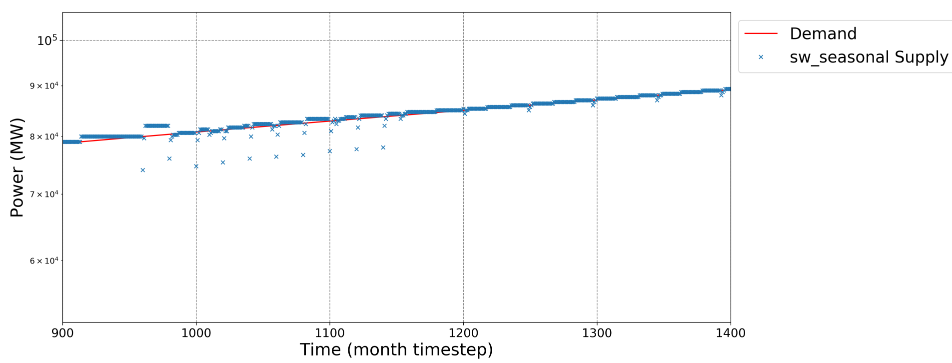


Figure 17: Linearly increasing power demand ($60000 + 250t/12MW$) and power supply obtained with the SO algorithms.

Table 7: Undersupply and oversupply of Power for the different prediction algorithms used to calculate EG01-EG24.

Algorithm	Undersupplied Timesteps	Cumulative Undersupply [GW.mo]	Cumulative Oversupply [GW.mo]
MA	36	313.7	840.9
ARMA	36	313.7	840.9
ARCH	36	316.8	859.0
POLY	65	282.4	1974.7
EXP_SMOOTHING	37	373.4	828.7
HOLT-WINTERS	37	373.4	828.7
FFT	20	315.1	2019.1
SW_SEASONAL	107	318.8	579.09

3.2 Buffer

This section presents a sensitivity analysis for varying power buffer values. Figure 18 shows a comparison of the cumulative undersupply for different buffer sizes using the fft prediction method. Figure 19 displays the power demand and supply for different values of the buffer using fft. The cumulative undersupply decreases with the increasing values of the buffer until it reaches an asymptotic value. That value is due to the undersupply at the beginning of the scenario, when the buffer size does not considerably impact the undersupply.

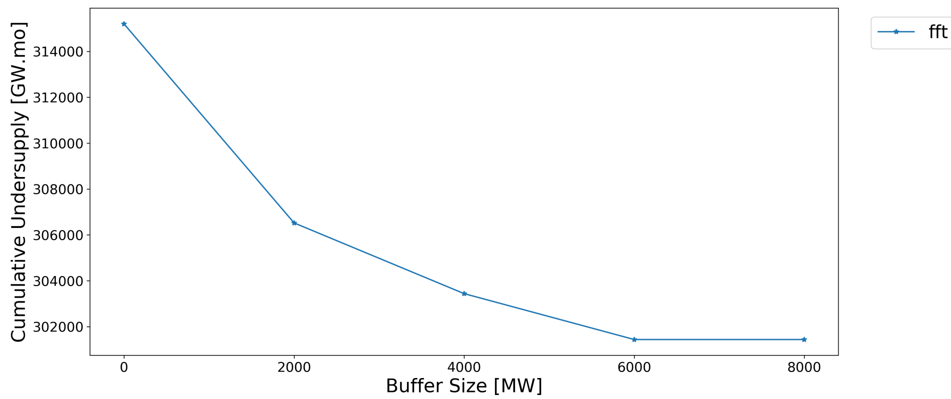


Figure 18: Sensitivity analysis for different buffer sizes using the fft prediction method.

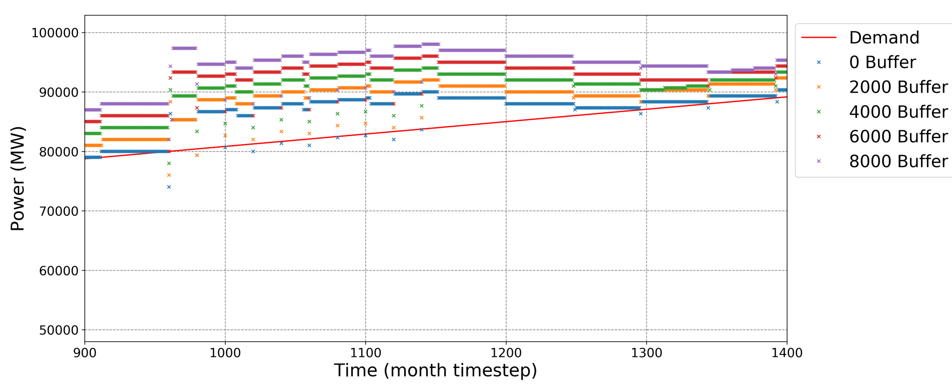


Figure 19: Power supply for different buffer sizes using the fft prediction method.

4 Eg01-Eg29

Figure 20 shows the facility and mass flow of transition scenario Eg01-Eg29 in CYCLUS.

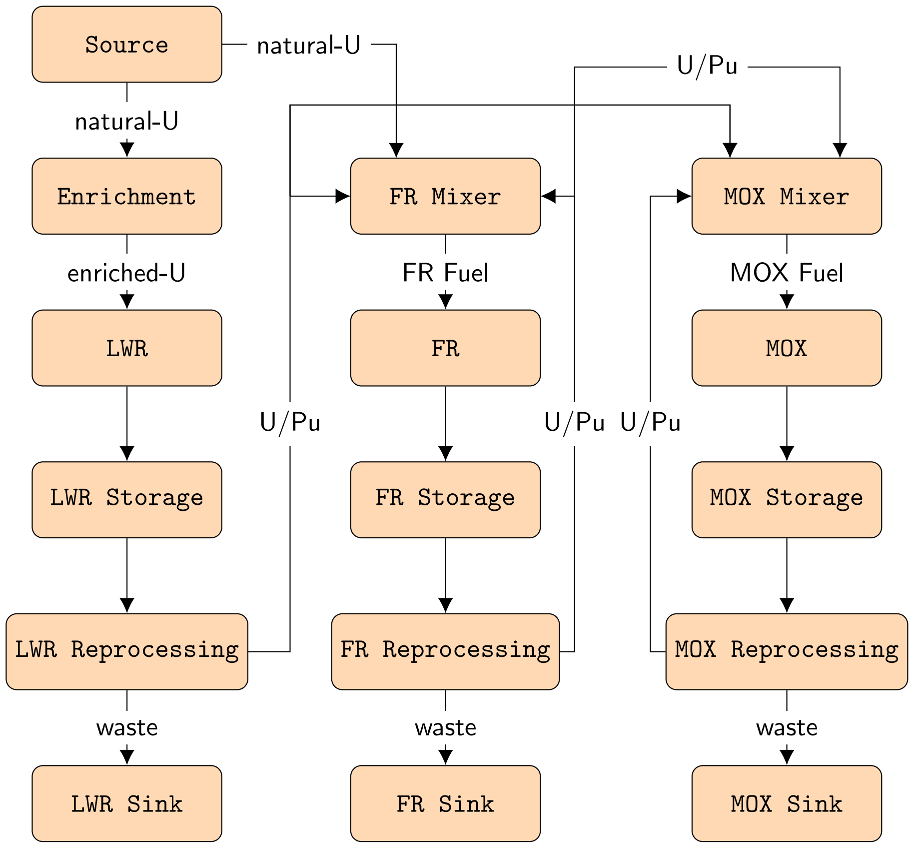


Figure 20: Diagram with facilities and mass flow of the scenario EG01-EG29.

4.1 Flat Power Demand: Power

This section presents plots of power for all the prediction methods. The power demand is 60000 MW throughout the simulation. Table 8 shows the input parameters. Figures 21, 22, and 23 display the power demand supply for the Non-optimizing (NO), Deterministic-optimizing (DO), and Stochastic-optimizing methods (SO), respectively. Table 9 records the number of steps with undersupply, the cumulative undersupply, and the cumulative oversupply. The smallest cumulative undersupply and smallest amount of undersupply time steps are for poly and fft prediction methods.

Table 8: EG01-EG29 input file values.

Parameter	Input
Demand equation [GW]	60
Deployment Driving Method	Installed Capacity
Power Buffer [MW]	0
Forward Steps	1
Backward Steps	2

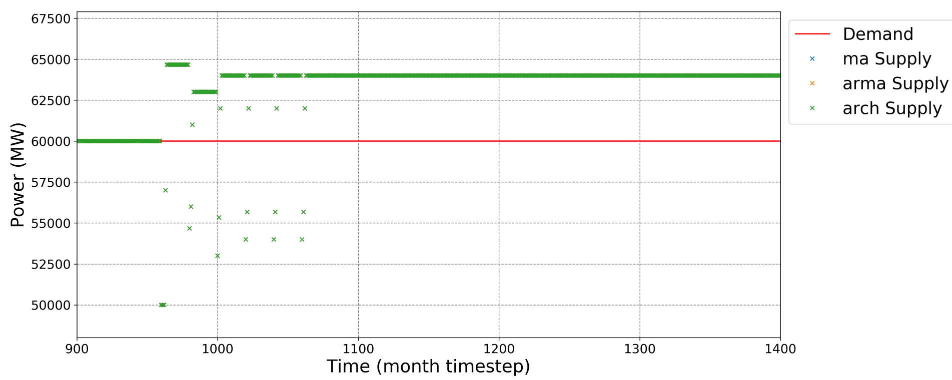


Figure 21: Constant power demand of 60GW and power supply obtained with the NO algorithms.

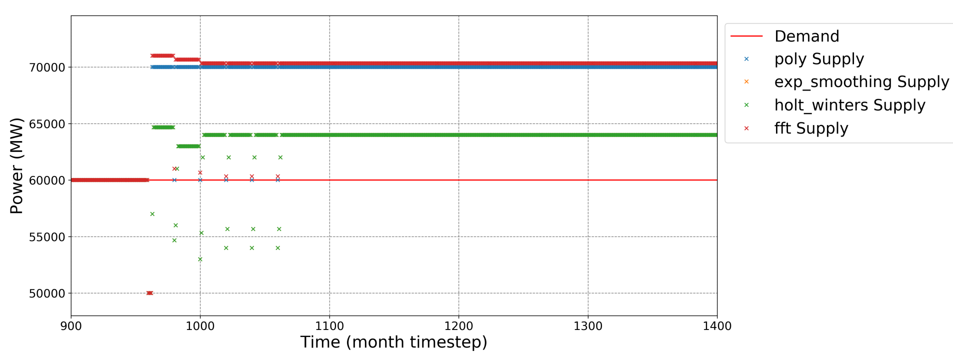


Figure 22: Constant power demand of 60GW and power supply obtained with the DO algorithms.

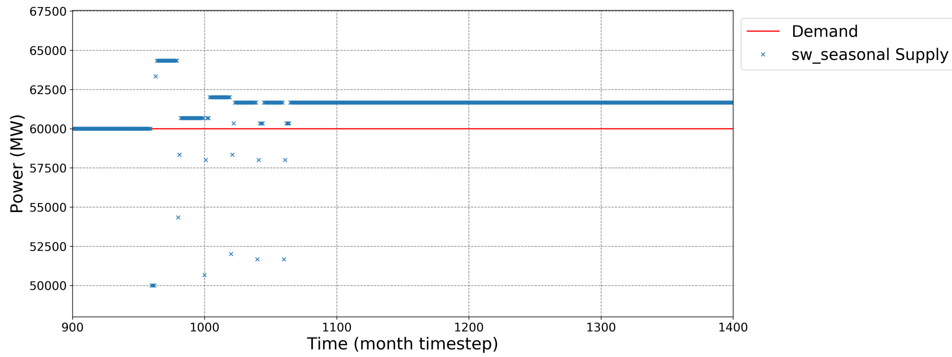


Figure 23: Constant power demand of 60GW and power supply obtained with the SO algorithms.

Table 9: Undersupply and oversupply of Power for the different prediction method used in EG01-EG29 simulations.

Algorithm	Undersupplied Timesteps	Cumulative Undersupply [GW.mo]	Cumulative Oversupply [GW.mo]
MA	15	145.0	1847.0
ARMA	15	145.0	1847.0
ARCH	15	145.0	1846.9
POLY	4	90.0	4720.3
EXP_SMOOTHING	16	205.0	1847.0
HOLT-WINTERS	16	205.0	1847.0
FFT	5	150.0	4898.0
SW_SEASONAL	14	139.0	798.9

4.2 Flat Power Demand: Meaningful commodities

Using the best prediction method, poly, this section presents plots for the supply and demand of the most meaningful commodities in the transition scenario. Table 10 summarizes which commodity each figure in this section corresponds to. Table 11 presents the number of steps of undersupply, cumulative undersupply, and cumulative oversupply of such commodities.

Table 10: Commodity names used in the simulation of EG01-EG29.

Commodity	Figure
Power	24
Natural-U	25a
Enriched-U	25b
FR fuel	26a
MOX LWR fuel	26b
Reprocessed Pu from spent fuel of LWRs	27
Reprocessed Pu from spent fuel of FRs	28a
Reprocessed Pu from spent fuel of MOX LWRs	28b

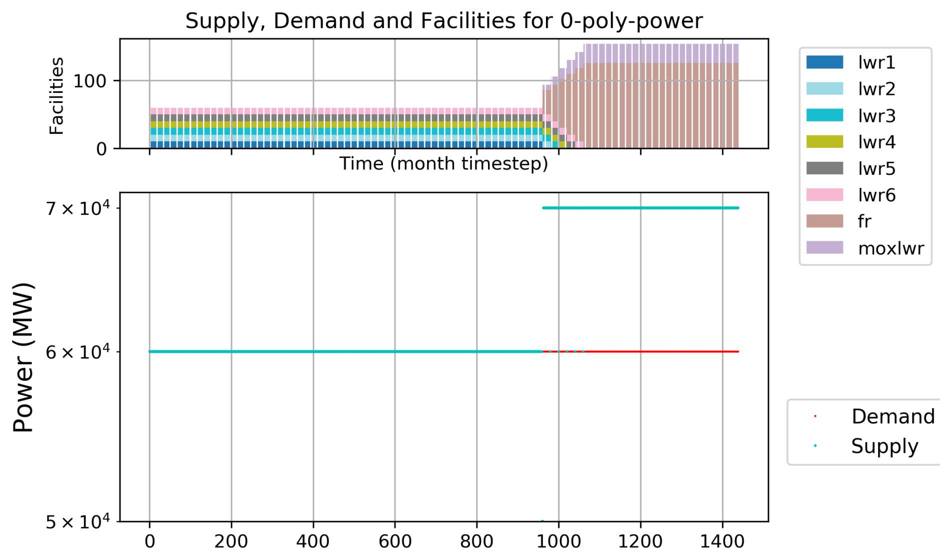
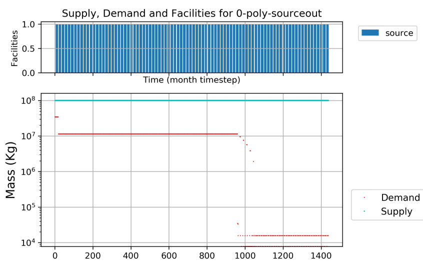
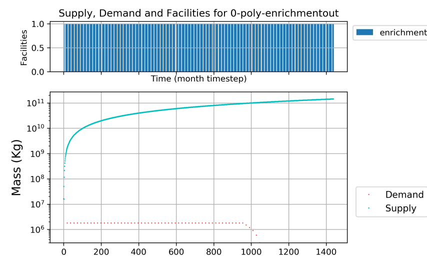


Figure 24: Demand and supply of Power and number of reactors deployed.

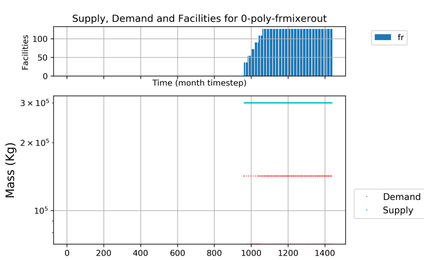


(a) Natural-U.

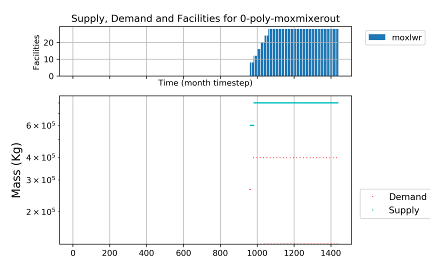


(b) Enriched-U.

Figure 25: Demand and supply of different commodities and number of facilities that produce them.



(a) FR Fuel.



(b) MOX LWR Fuel.

Figure 26: Demand and supply of fuel and number of reactors.

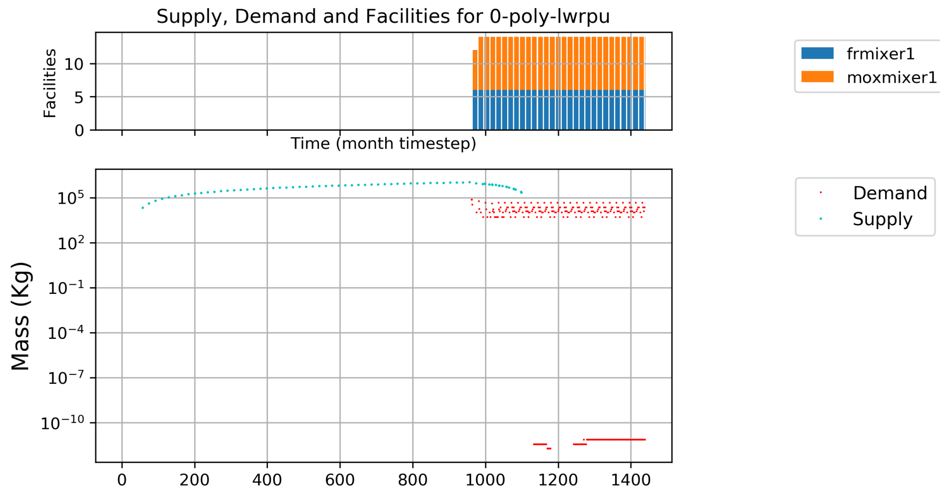
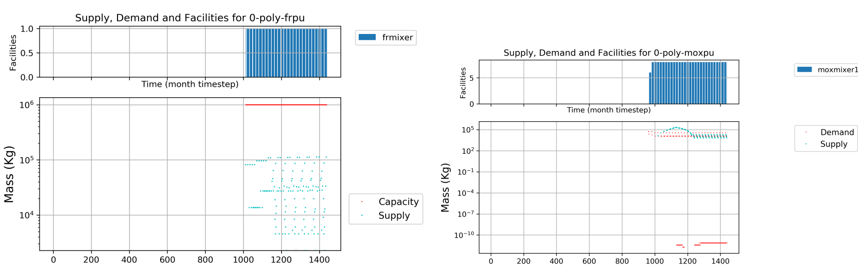


Figure 27: Demand and supply of reprocessed Pu from spent fuel of LWRs and number of facilities supplied with them.



(a) Reprocessed Pu from spent fuel of FRs.

(b) Commodity moxpu.

Figure 28: Demand and supply of different commodities and number of facilities supplied with them.

Table 11: Undersupply and oversupply of different commodities using poly to calculate EG01-EG29.

Commodity	Undersupplied Timesteps	Cumulative Undersupply [10^3Kg]	Cumulative Oversupply [10^6Kg]
Natural-U	1	34394.0	132319869.5
Enriched-U	1	16126.1	102751545581.6
FR Fuel	2	284.4	124827.3
MOX LWR Fuel	2	530.1	354541.5

5 Eg01-Eg30

Figure 29 shows the facility and mass flow of transition scenario Eg01-Eg30 in CYCLUS.

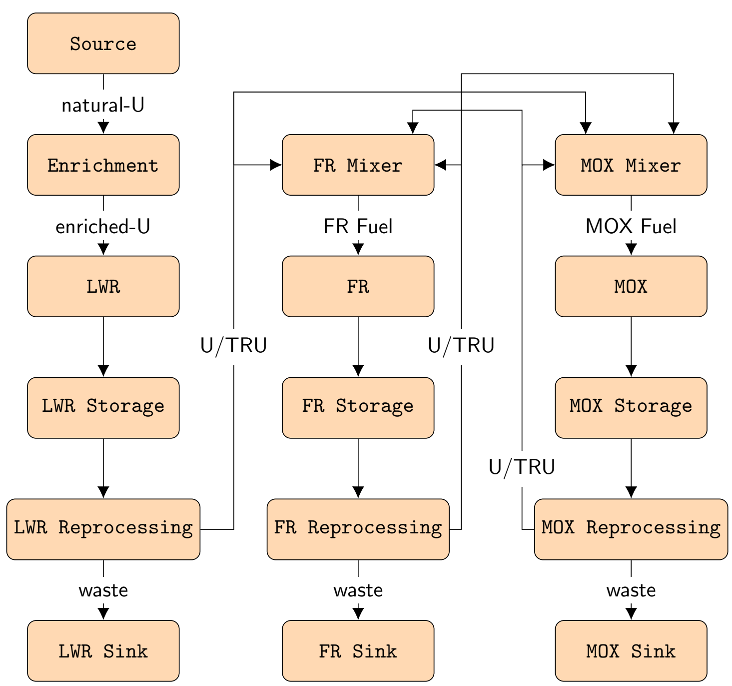


Figure 29: Diagram with facilities and mass flow of the scenario EG01-EG30.

5.1 Linearly increasing Power Demand: Power

This section presents plots of power for all the prediction methods. The power demand increases linearly with the expression $60000 + 250t/12MW$. Table 12 shows the input parameters. Figures 30, 31, and 32 display the power supply and demand. The plots only show the power demand and supply during the transition period. Undersupply of power occur during two main time periods: initial demand for the commodity and during the transition period. Undersupply time steps occurring at the beginning of the simulation is expected since without time series data at the beginning of the simulation, `d3ploy` takes a few time steps to collect time series data about power demand to begin predicting and starting deployment of reactor and supporting fuel cycle facilities. Table 13 records the number of steps of undersupply, the cumulative undersupply, and the cumulative oversupply. The smallest cumulative undersupply and smallest amount of undersupply time steps are for poly and fft prediction methods.

Table 12: EG01-EG30 input file values.

Parameter	Input
Demand equation [MW]	60000 + 250t/12
Deployment Driving Method	Installed Capacity
Buffer	0
Forward Steps	1
Backward Steps	2

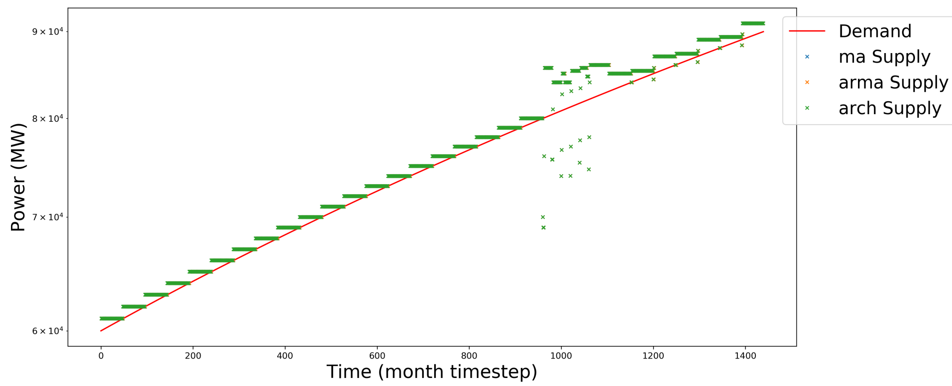


Figure 30: Linearly increasing power demand ($60000 + 250t/12MW$) and power supply obtained with the NO algorithms.

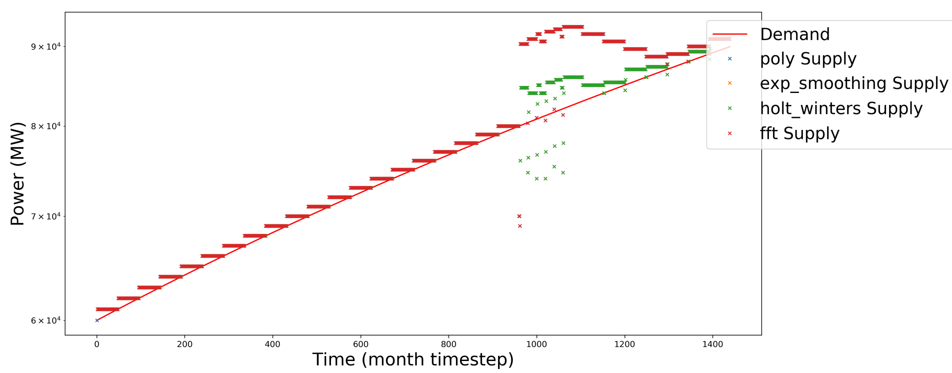


Figure 31: Linearly increasing power demand ($60000 + 250t/12MW$) and power supply obtained with the DO algorithms.

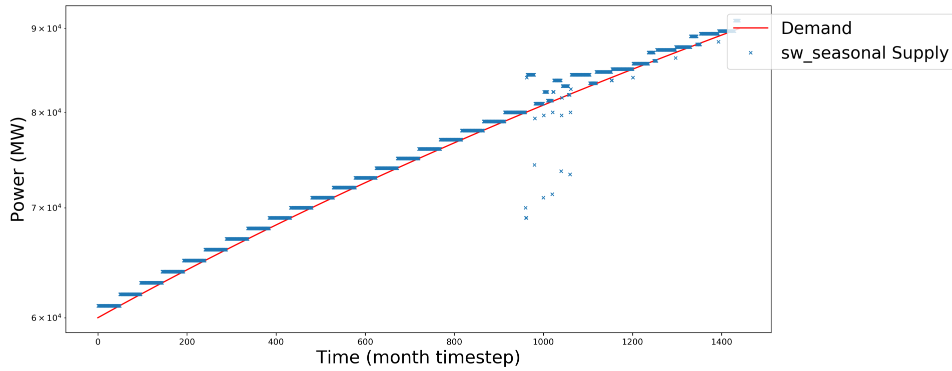


Figure 32: Linearly increasing power demand ($60000 + 250t/12MW$) and power supply obtained with the SO algorithms.

Table 13: Undersupply and oversupply of Power for the different prediction algorithms used to calculate EG01-EG24.

Algorithm	Undersupplied Timesteps	Cumulative Undersupply [GW.mo]	Cumulative Oversupply [GW.mo]
MA	24	152.3	1334.1
ARMA	24	152.3	1334.1
ARCH	21	152.1	1355.9
POLY	9	92.5	3073.1
EXP_SMOOTHING	25	211.6	1317.8
HOLT-WINTERS	25	211.6	1317.8
FFT	9	152.5	3079.4
SW_SEASONAL	51	147.3	873.4

6 Summary

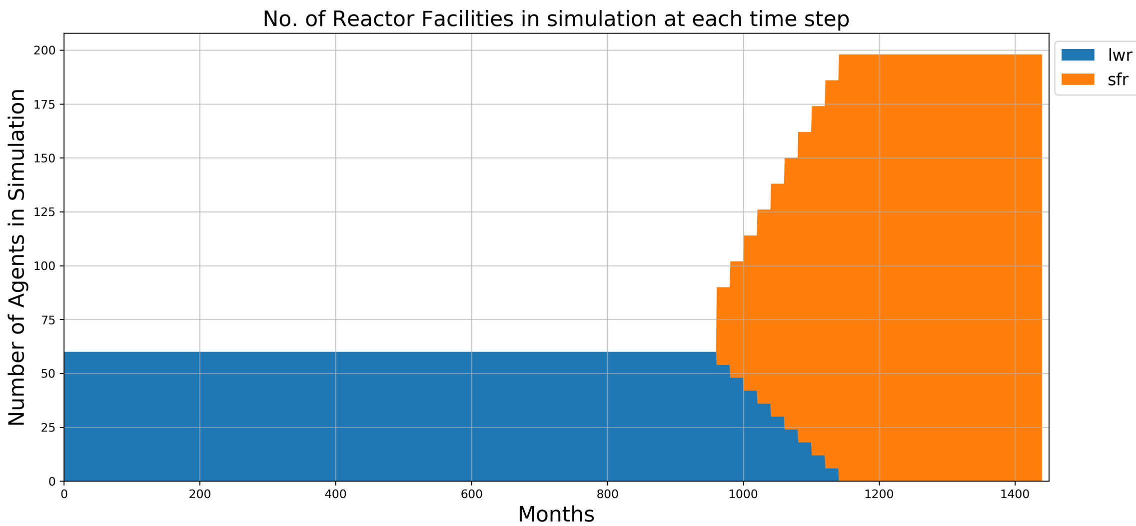
By utilizing the sensitivity analysis and transition scenario set up in the previous sections, we determined the `d3ploy` input parameters for EG01-EG23, EG01-EG24, EG01-EG29, and EG01-EG30 that minimize undersupply of power and minimize the undersupply and under capacity of the other commodities in the simulation. Table 14 shows `d3ploy` input parameters. The need for buffers for commodities is a reflection of reality in which

	Input Parameter	Simulation Description			
		EG01-23	EG01-24	EG01-29	EG01-30
Required	Demand driving commodity	Power			
	Demand equation [MW]	60000	$60000 + 250t/12$	60000	$60000 + 250t/12$
	Prediction method	`poly`	`fft`	`poly`	`fft`
	Deployment Driving Method	Installed Capacity			
Optional	Buffer type	Absolute			
	Power Buffer size [MW]	0	6000	0	8000

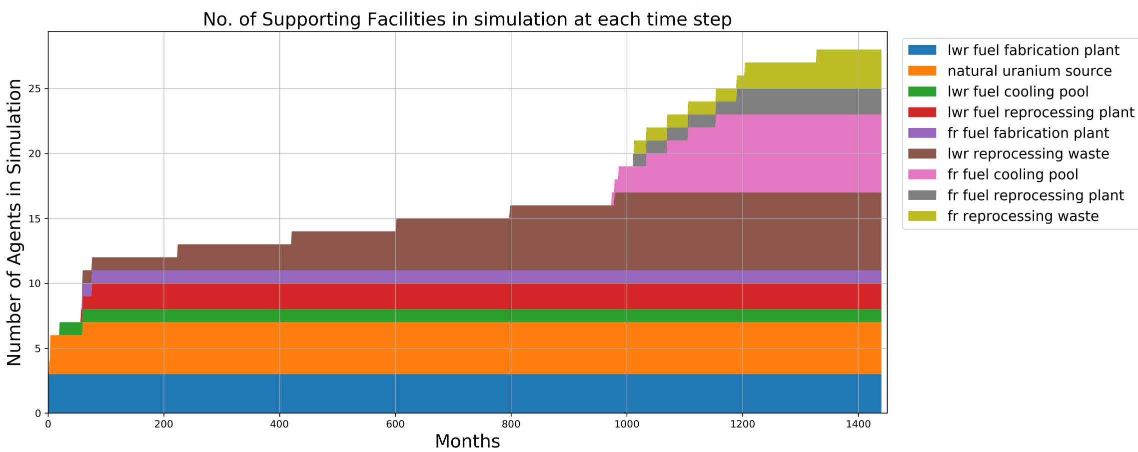
Table 14: `d3ploy`'s input parameters for EG01-EG23, EG01-EG24, EG01-EG29, and EG01-EG30 transition scenarios that minimizes undersupply of power and minimizes the undersupply and under capacity of the other facilities.

a supply buffer is usually maintained to ensure continuity in the event of an unexpected failure in the supply chain.

Figures 33, 34, 35, and 36 show time dependent deployment of reactor and supporting facilities for the EG01-23 constant power demand, EG01-24 linearly increasing power demand, EG01-29 constant power demand, EG01-30 linearly increasing power demand transition scenarios, respectively. `d3ploy` automatically deploys reactor and supporting facilities to setup a supply chain to meet power demand during a transition from Light Water Reactors (LWRs) to Sodium-Cooled Fast Reactors (SFRs) for EG01-23 and EG01-24, and from LWRs to mixed oxide (MOX) LWRs and SFRs for EG01-29 and EG01-30.

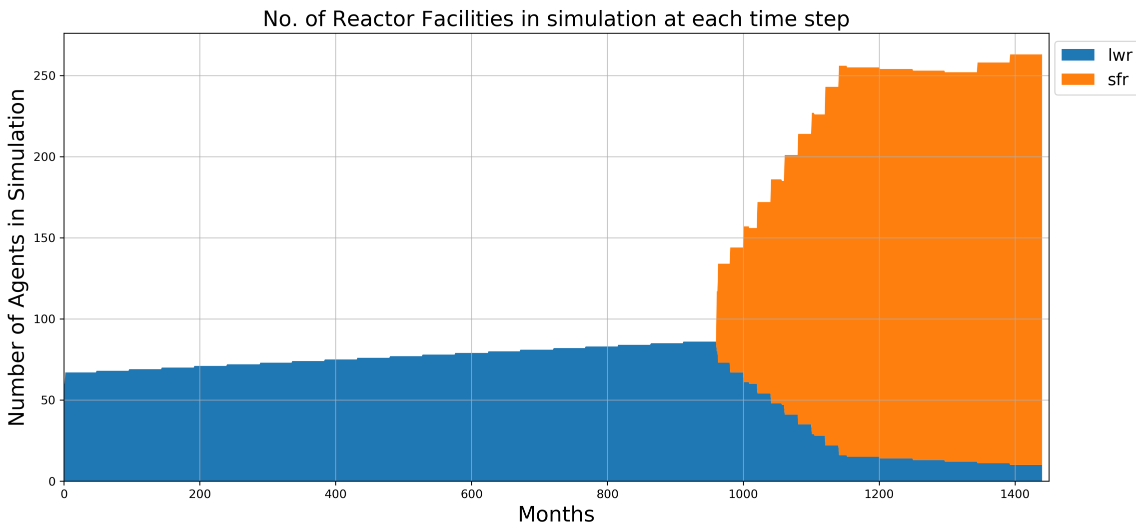


(a) EG01-23: Reactor Deployment

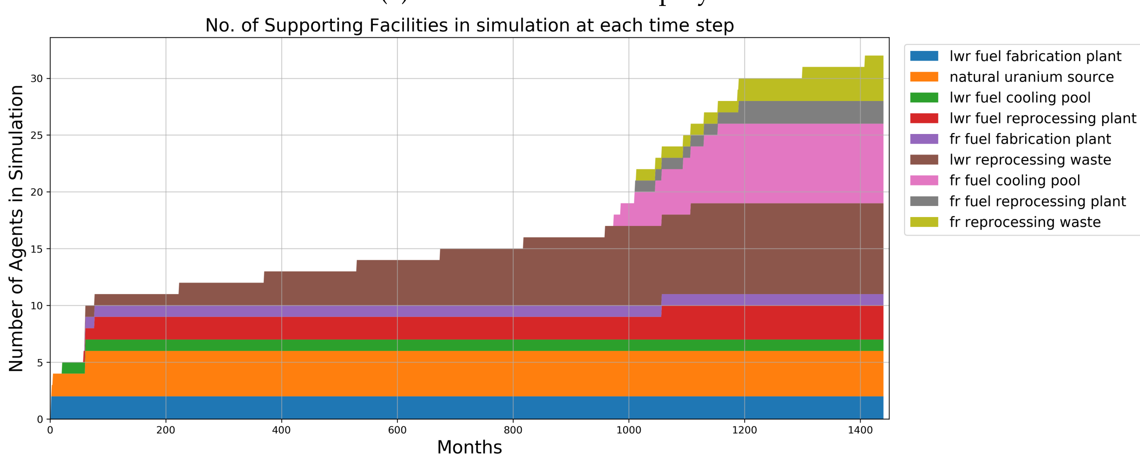


(b) EG01-23: Supporting Facility Deployment

Figure 33: Time dependent deployment of reactor and supporting facilities in the EG01-23 constant power demand transition scenario. `d3ploy` automatically deploys reactor and supporting facilities to setup a supply chain to meet constant power demand of 60000 MW during a transition from LWRs to SFRs.

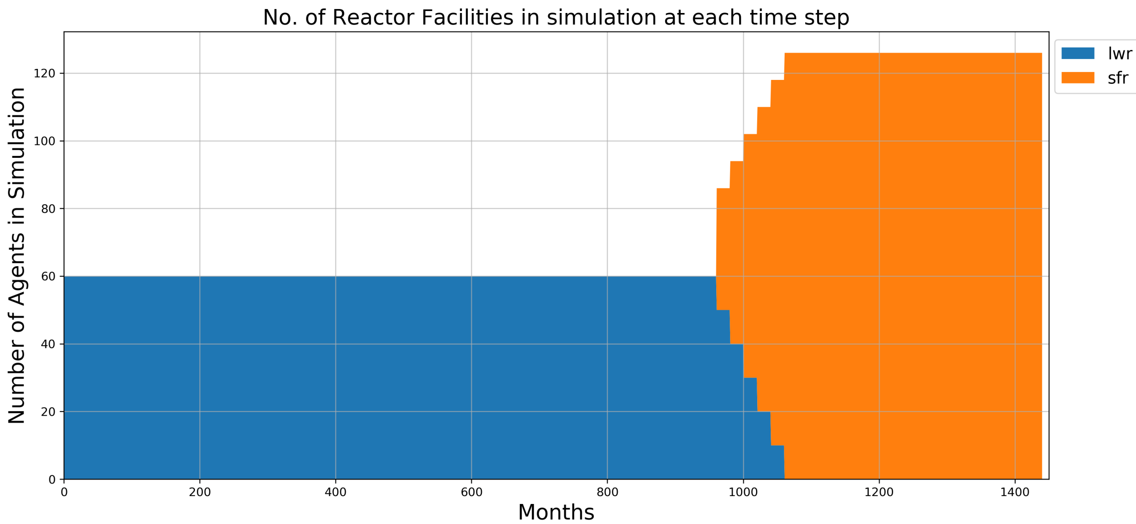


(a) EG01-24: Reactor Deployment

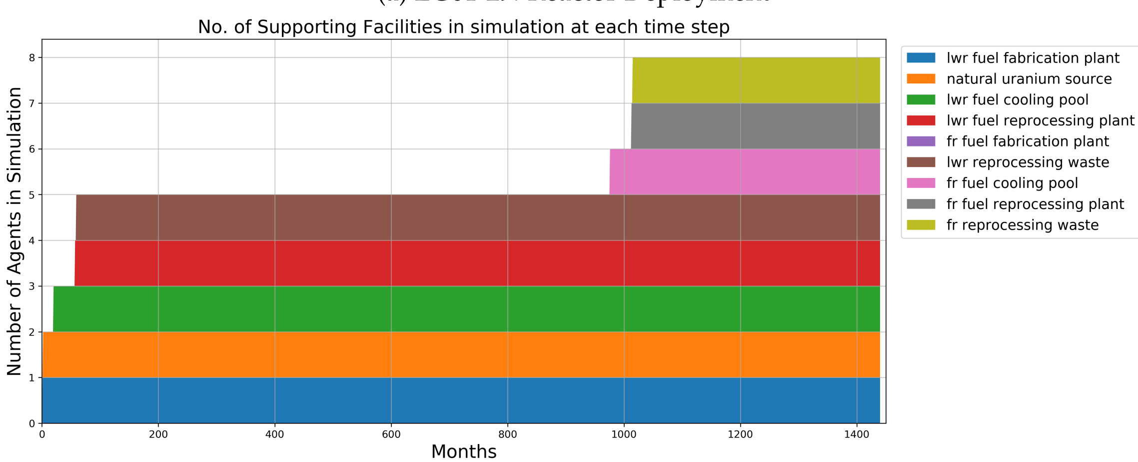


(b) EG01-24: Supporting Facility Deployment

Figure 34: Time dependent deployment of reactor and supporting facilities in the EG01-24 linearly increasing power demand transition scenario. `d3ploy` automatically deploys reactor and supporting facilities to setup a supply chain to meet linearly increasing power demand of $60000 + 250t/12$ MW during a transition from LWRs to SFRs.

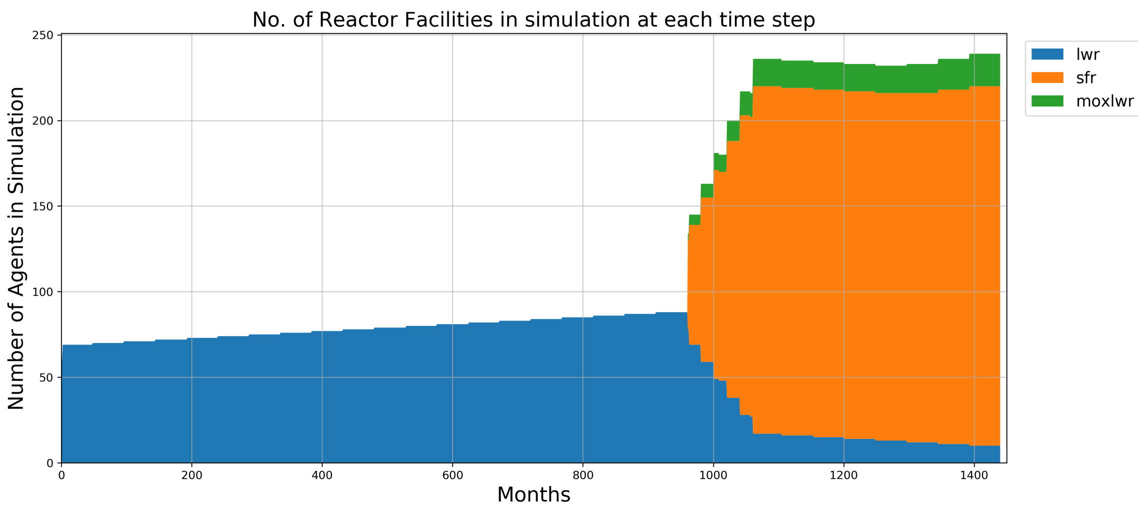


(a) EG01-29: Reactor Deployment

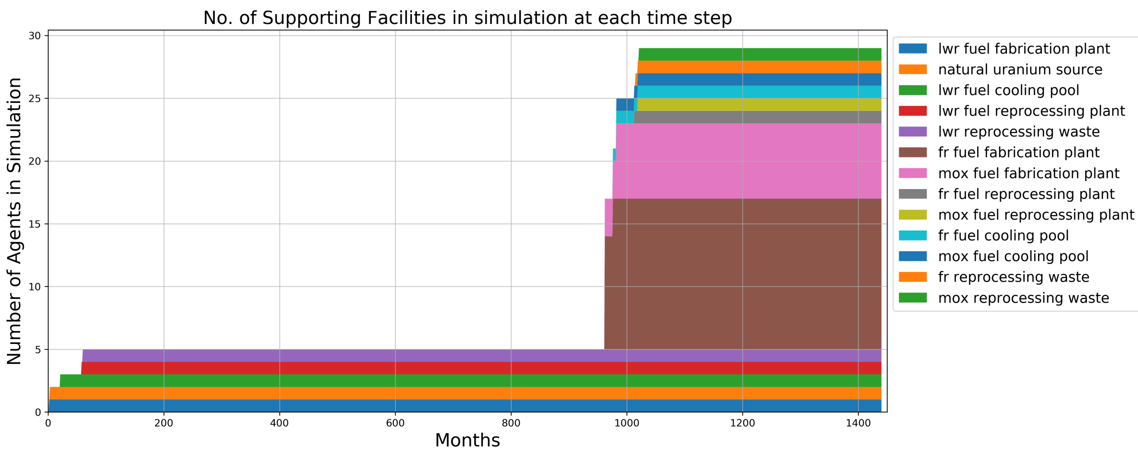


(b) EG01-29: Supporting Facility Deployment

Figure 35: Time dependent deployment of reactor and supporting facilities in the EG01-29 linearly increasing power demand transition scenario. `d3ploy` automatically deploys reactor and supporting facilities to setup a supply chain to meet constant power demand of 60000 MW during a transition from LWRs to MOX LWRs and SFRs.



(a) EG01-30: Reactor Deployment



(b) EG01-30: Supporting Facility Deployment

Figure 36: Time dependent deployment of reactor and supporting facilities in the EG01-30 linearly increasing power demand transition scenario. `d3ploy` automatically deploys reactor and supporting facilities to setup a supply chain to meet linearly increasing power demand of $60000 + 250t/12$ MW during a transition from LWRs to MOX LWRs and SFRs.

References

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URL https://fuelcycleevaluation.inl.gov/Shared%20Documents/ES%20Main%20Report.pdf

[2] arfc/d3ploy: A collection of Cyclus manager archetypes for demand driven deployment, 10.5281/zenodo.3464123 (Sep. 2019).
URL https://github.com/arfc/d3ploy