

# Revealing the Oil Majors' Adaptive Capacity to the Energy Transition with Deep Multi-Agent Reinforcement Learning

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A photograph of an offshore oil and gas platform in the foreground, with several wind turbines visible in the background across the water. The sky is overcast.

# Outline

Introduction

Solving a Wargame

2DP-MARL

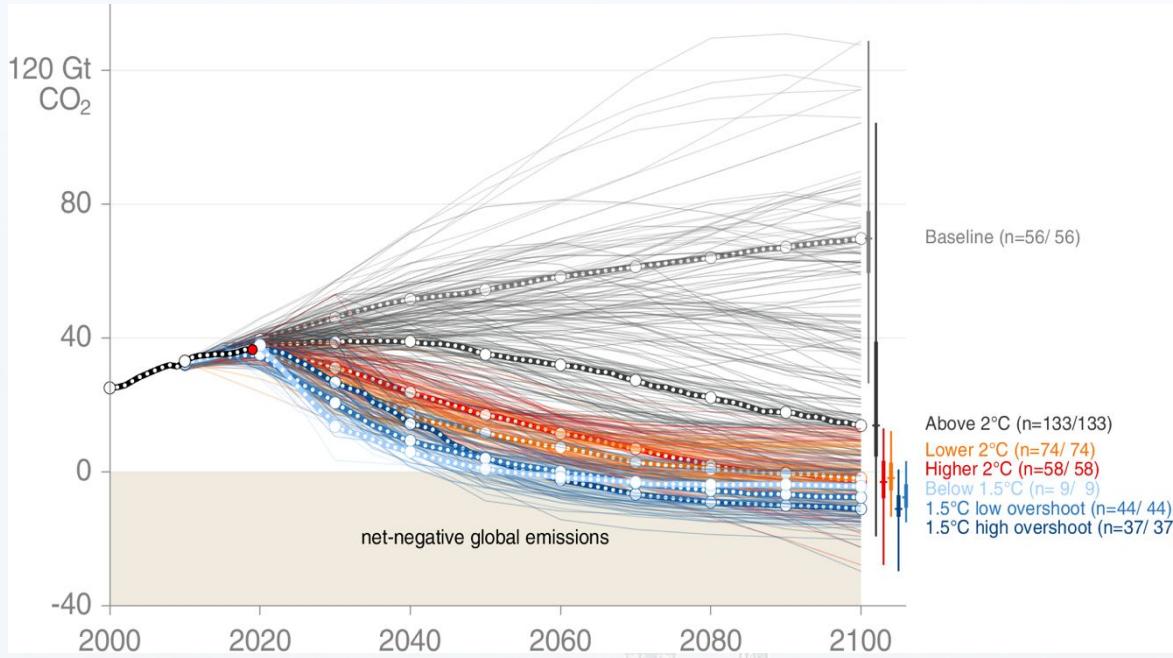
Results & Analysis

Impact

Future Work

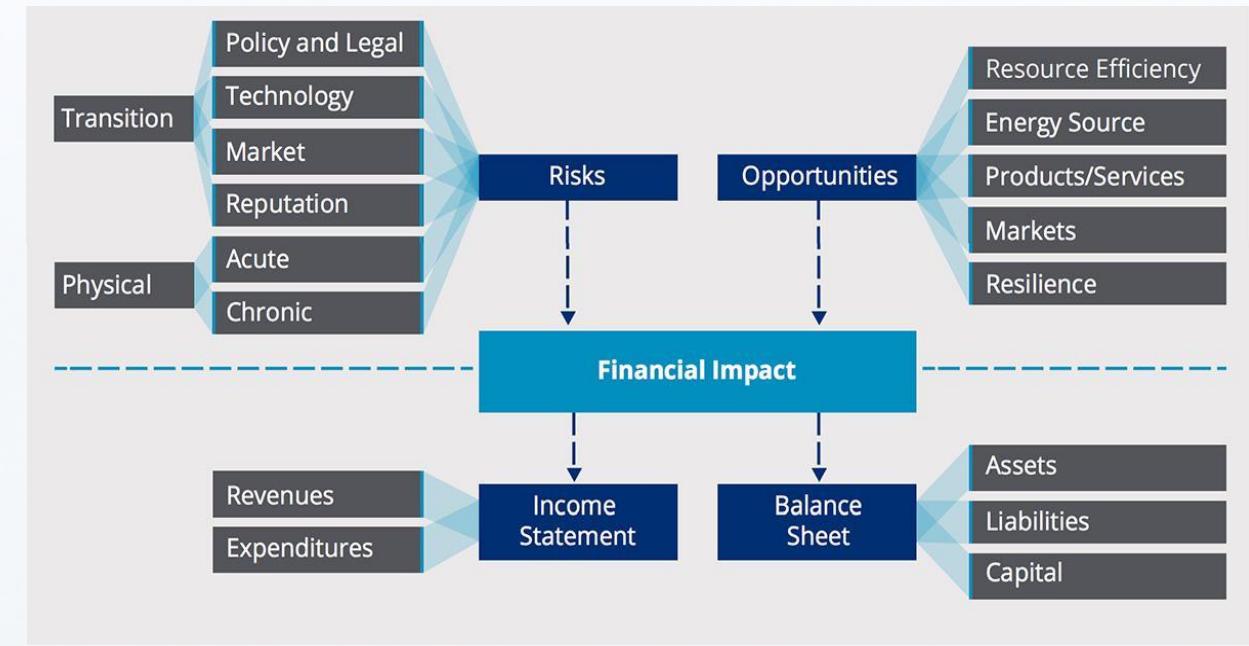
# Introduction





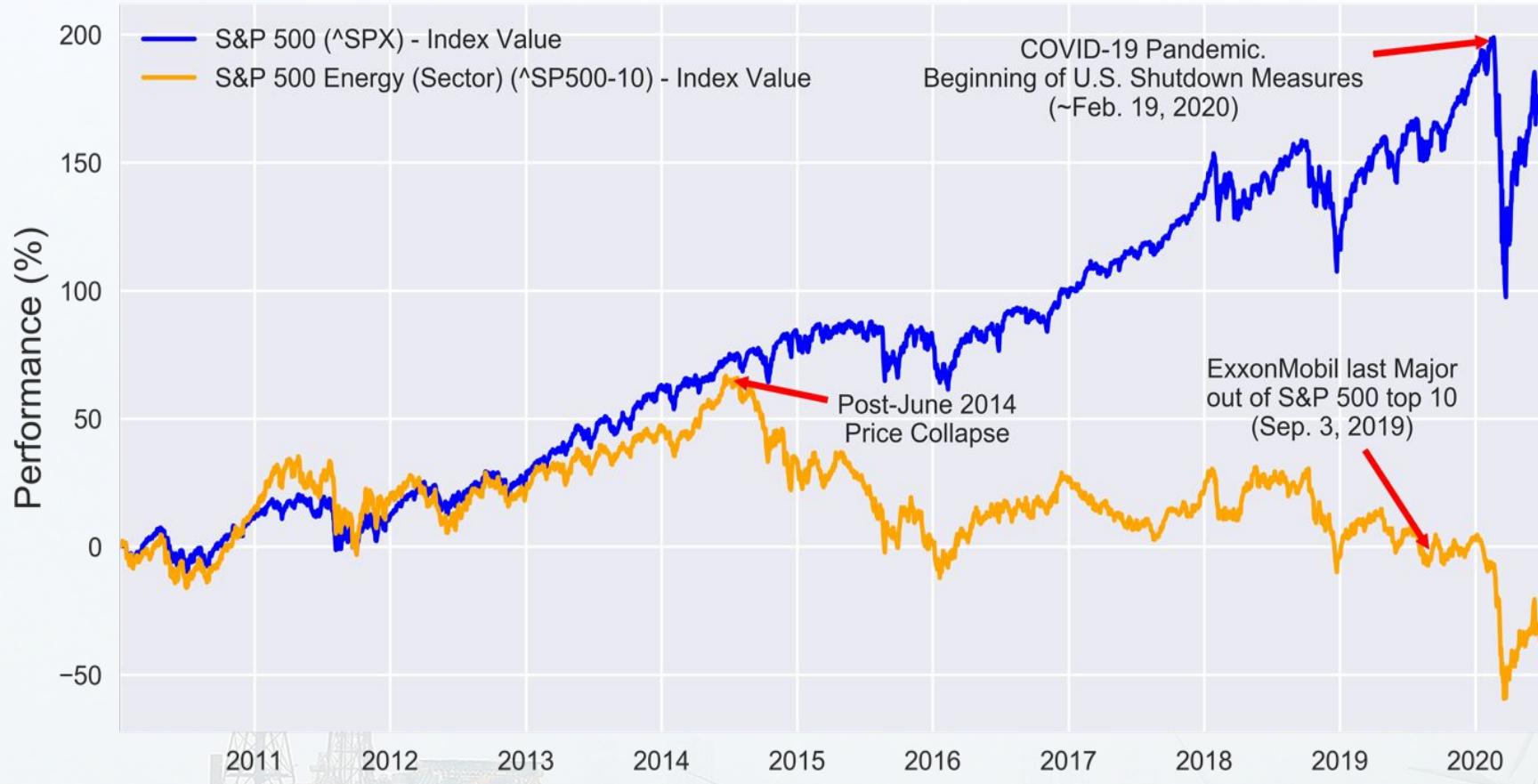
## Energy transition manifesting in response to climate change

- Though pathways vary, all scenarios predicated on low-carbon energy production
- Deep decarbonization requires massive reallocation of capital



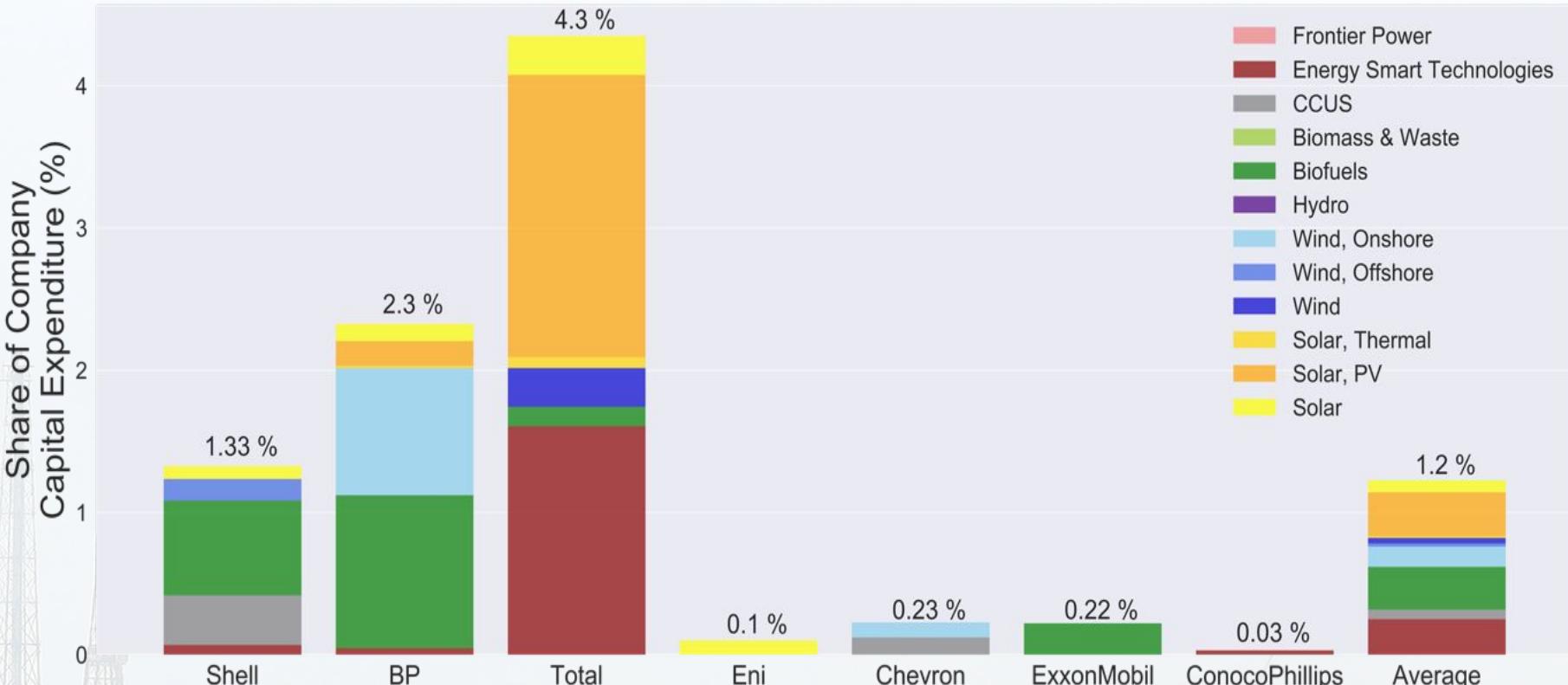
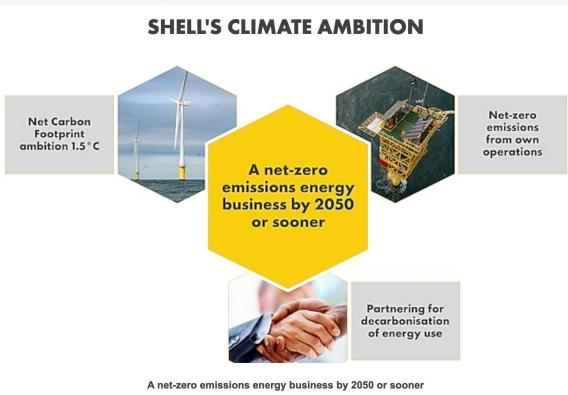
## Transition risks will arise, however, so will opportunities

- Rapid low-carbon transition poses an existential threat for the fossil fuel industry, particularly the oil Majors
- Adaptation may prove financially favorable



**The Majors have been in decline since 2014, COVID-19 has accelerated it**

- Oil & gas companies have consistently underperformed despite economic growth
- Financial recovery post-COVID through BAU becomes increasingly unlikely as the impeding energy transition unfolds



## Low-carbon actions speak louder than net-zero words

- Majors have set out plans for a full-scale decarbonization of their business models
- Throughout the previous decade, the Majors' low-carbon efforts proved minimal
- Majors have yet to make significant moves into low-carbon business models as the upside and downside risks of doing so remain unclear

# Aim

Provide tangible insights into the Majors' adaptive capacity to the energy transition by

*Exploring upside and downside risks of a first low-carbon mover*



*Solving for robust business pathways amidst energy transition uncertainty*



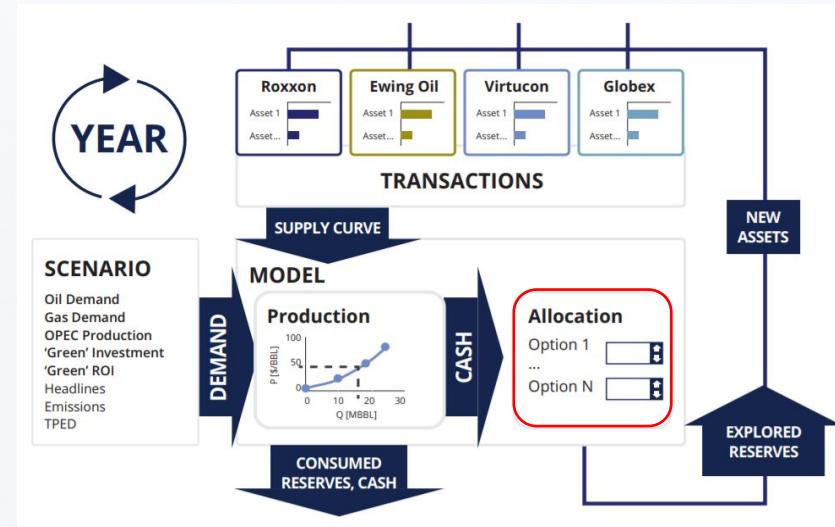
# Solving a Wargame



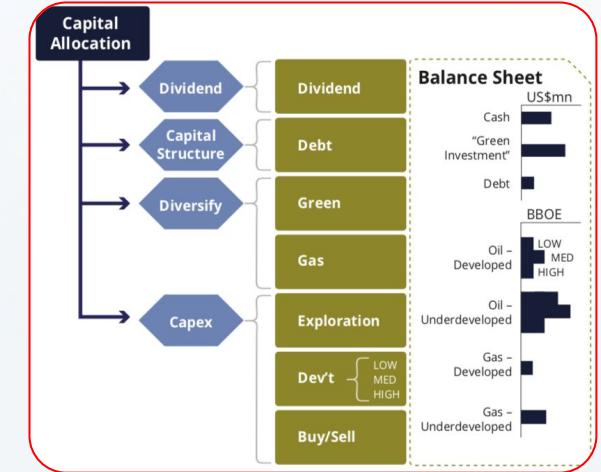
MARCH 2018

# CRUDE AWAKENING: MAKING OIL MAJOR BUSINESS MODELS CLIMATE-COMPATIBLE

BEN CALDECOTT, INGRID HOLMES, LUCAS KRUITWAGEN,  
DILEIMY OROZCO AND SHANE TOMLINSON



2DP Wargame Schematic



Player Allocation Options

## 2 Degrees Pathways Wargame – testbed for oil & gas transition

- The 2 Degrees Pathways (2DP) wargame created to

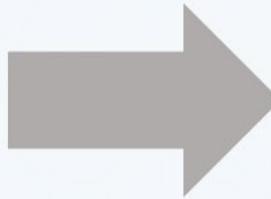
*“To help inform company, investor, government, and civil society thinking around pathways the oil and gas majors can take to become 1.5C/2C-compatible”*

- Originally played with human players, revealing more about human bias than robust, climate-compatible pathways

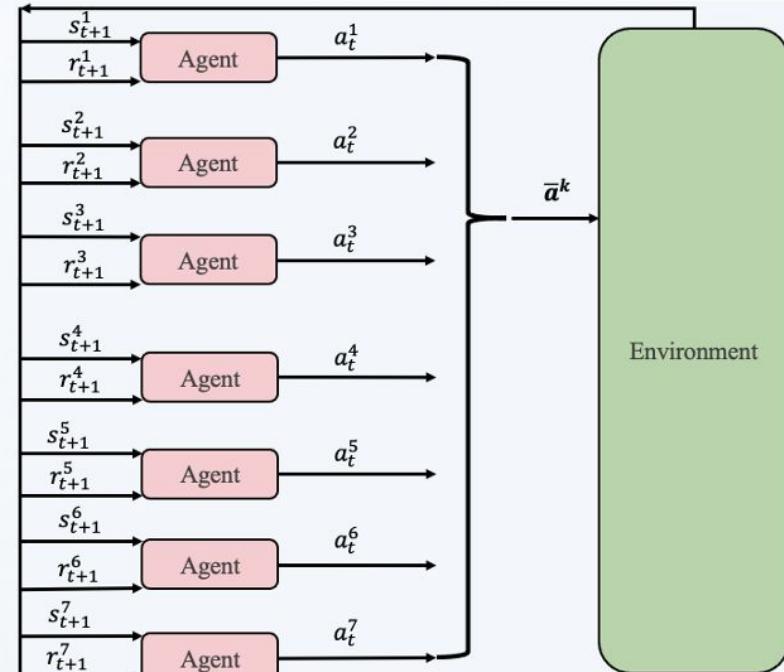
## Partially Observable Stochastic Game

$$\langle \mathcal{I}, \mathcal{S}, \{b^0\}, \{A_i\}, \{\mathcal{O}_i\}, \mathcal{P}, \{\mathcal{R}_i\} \rangle$$

Notation	Description
$\mathcal{I}$	Finite set of agents indexed $1, \dots, n$
$\mathcal{S}$	Finite set of states $\{s^1, \dots, s^N\}$
$b^0 \in \Delta(\mathcal{S})$	Initial state distribution
$A_i$	Finite set of actions available to agent $i$ and $\vec{A} = \times_{i \in \mathcal{I}} A_i$ is the set of joint actions (i.e. action profiles), where $\vec{a} = \langle a_1, \dots, a_n \rangle$ denotes the joint action
$\mathcal{O}_i$	Finite set of observations for agent $i$ and $\vec{\mathcal{O}} = \times_{i \in \mathcal{I}} \mathcal{O}_i$ is the set of joint observations where $\vec{o} = \langle o_1, \dots, o_n \rangle$ denotes the joint observation
$\mathcal{P}$	Set of Markovian state transition and observation probabilities, where $\mathcal{P}(s', \vec{o}   s, \vec{a})$ denotes the probability that taking joint action $\vec{a}$ in state $s$ results in a transition to state $s'$ and joint observation $\vec{o}$
$\mathcal{R}_i: \mathcal{S} \times \vec{\mathcal{A}}$	Reward function for agent $i$



## Multi-Agent Reinforcement Learning



## Framing 2DP as a Partially Observable Stochastic Game

- A continuous control problem with multiple competing entities, 2DP is best characterized as a Partially Observable Stochastic Game (POSG)—a Markovian framework resemblant of real-life market competition

## Solving with Deep Multi-Agent Reinforcement Learning

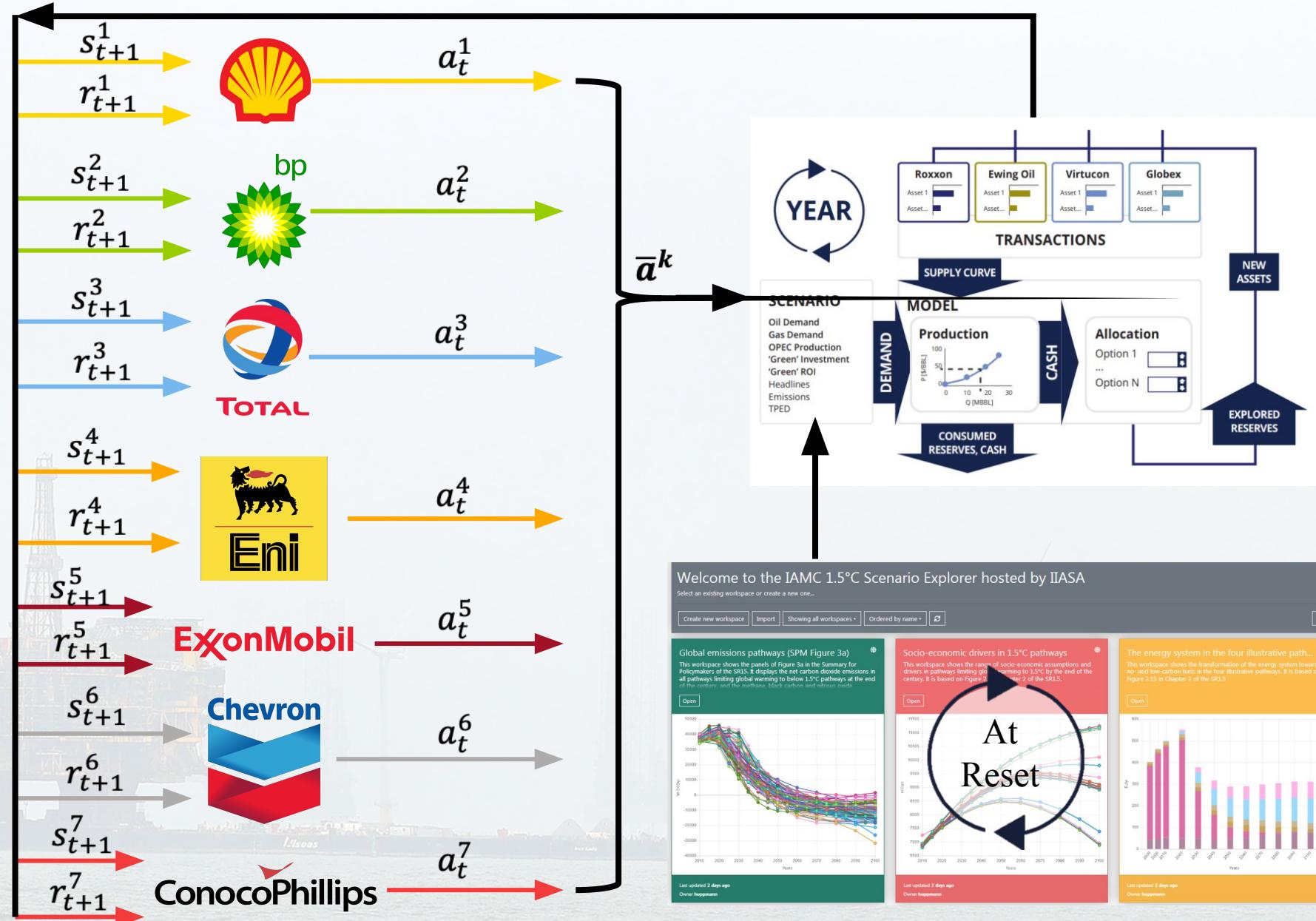
- Advances in Deep Multi-Agent Reinforcement Learning (MARL) have achieved superhuman-level performance in POSGs of high-dimensional settings

# 2DP-MARL



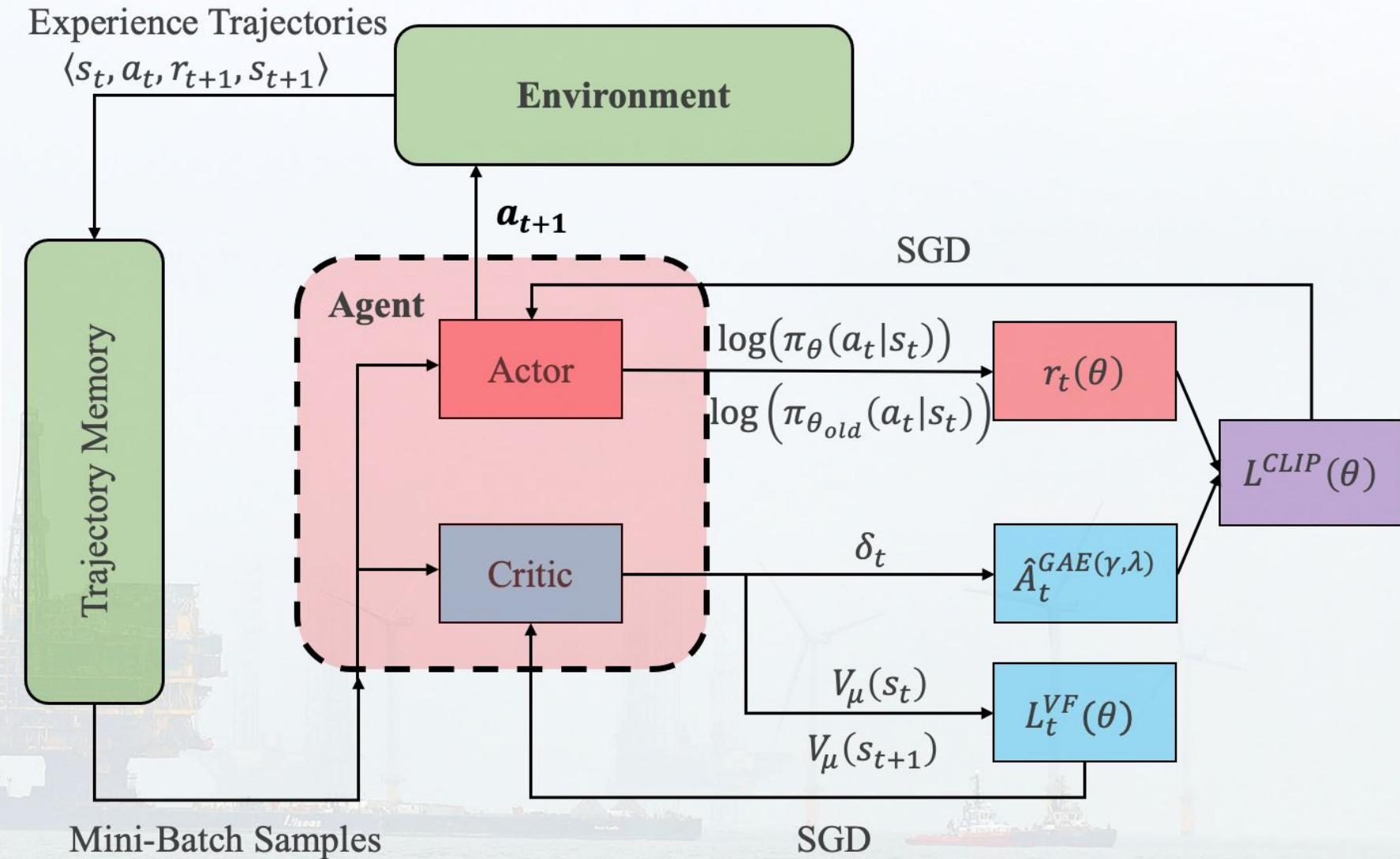
# A novel microeconomics model relevant to the energy transition discussion

- 2DP-MARL combines wargaming and advances in Deep MARL to help guide the Majors' stakeholders in assessing climate-compatible business models



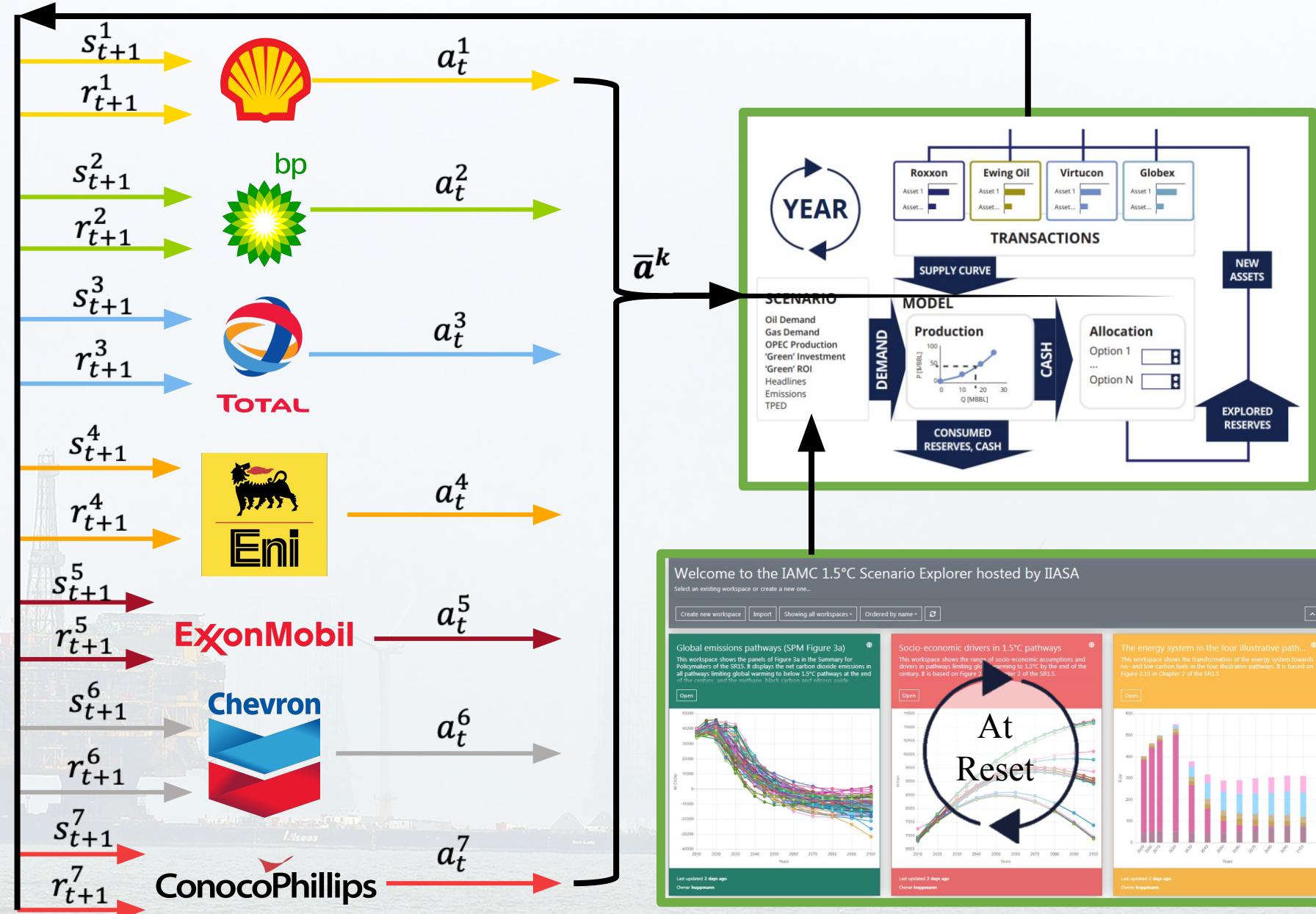
## A2C/PPO as foundational algorithms

- Algorithms employed take from Advantage Actor-Critic and Proximal Policy Optimization to solve a game in a high-dimensional, continuous space



## Environment

- Original 2DP Wargame, 2020-2040
- Climate-compatible scenario data generated from Integrated Assessment Modeling Consortium (IAMC) and International Institute for Applied Energy Systems (IIASA) ensemble

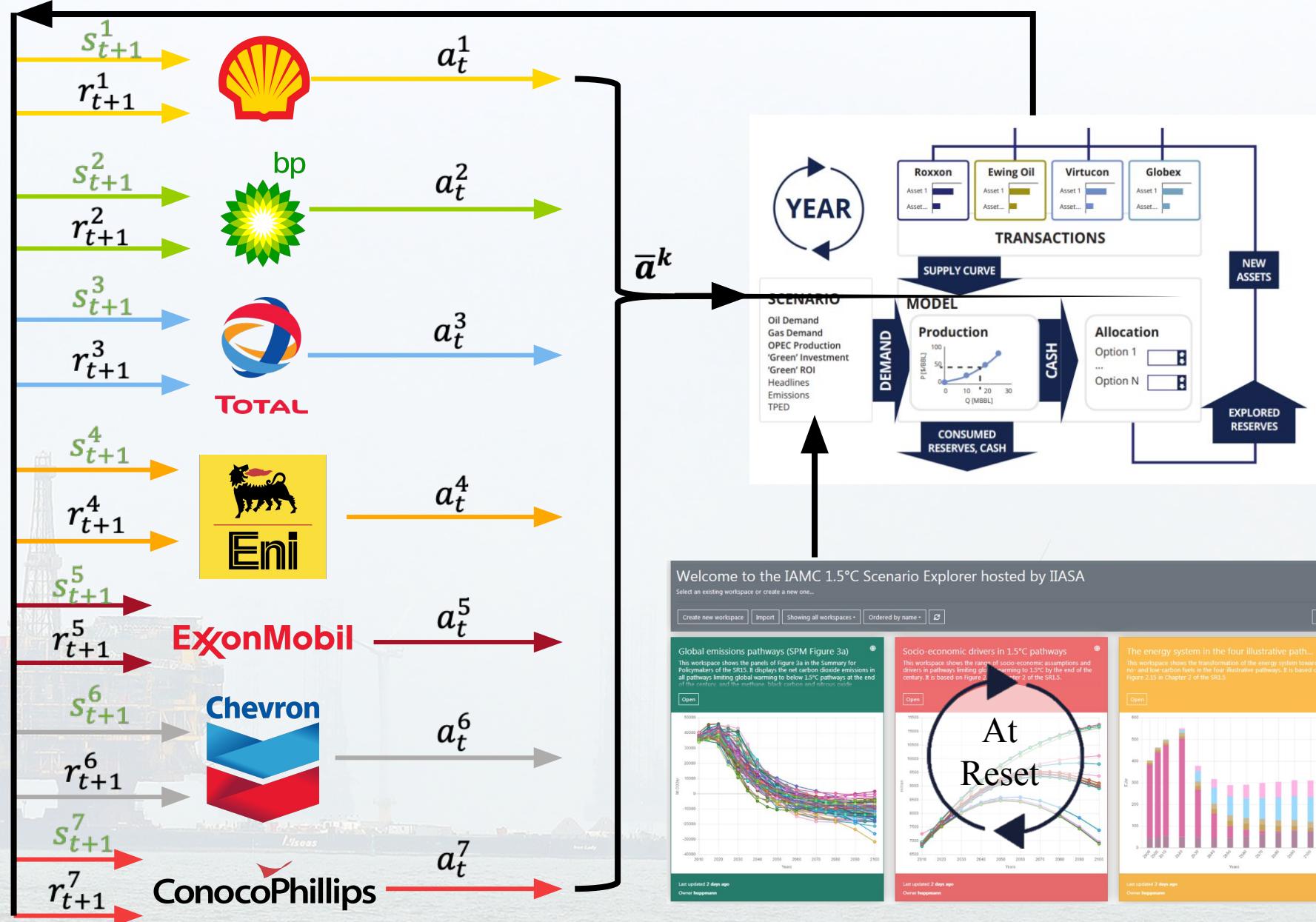


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## Observations

- Incomplete information to mimic real-life competition (i.e. players may only view some of their adversaries' assets)



## Environment

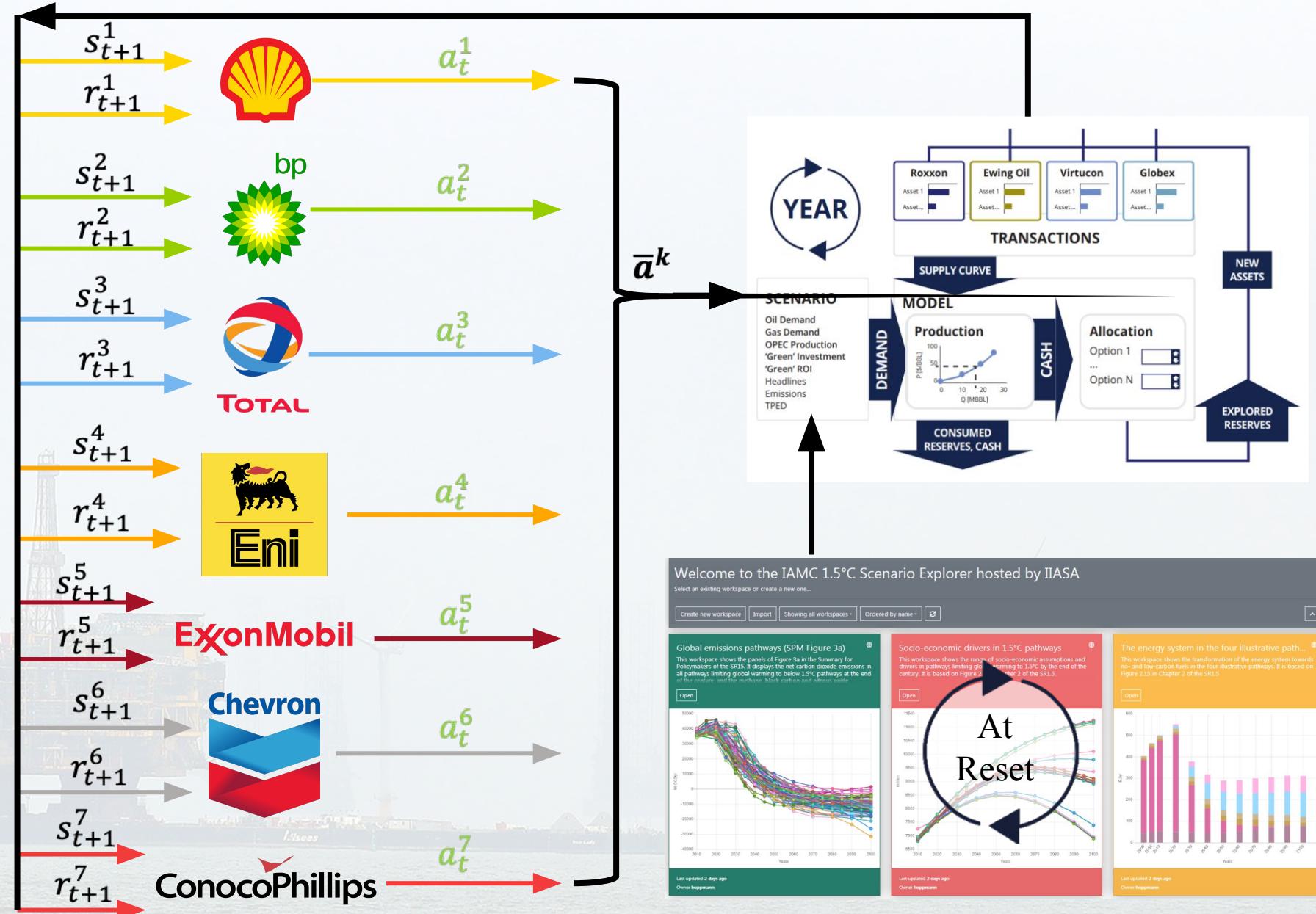
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## Actions

- Similar to 2DP wargame capital allocation options, includes player-to-player trading and 'green' auction house



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# Observations

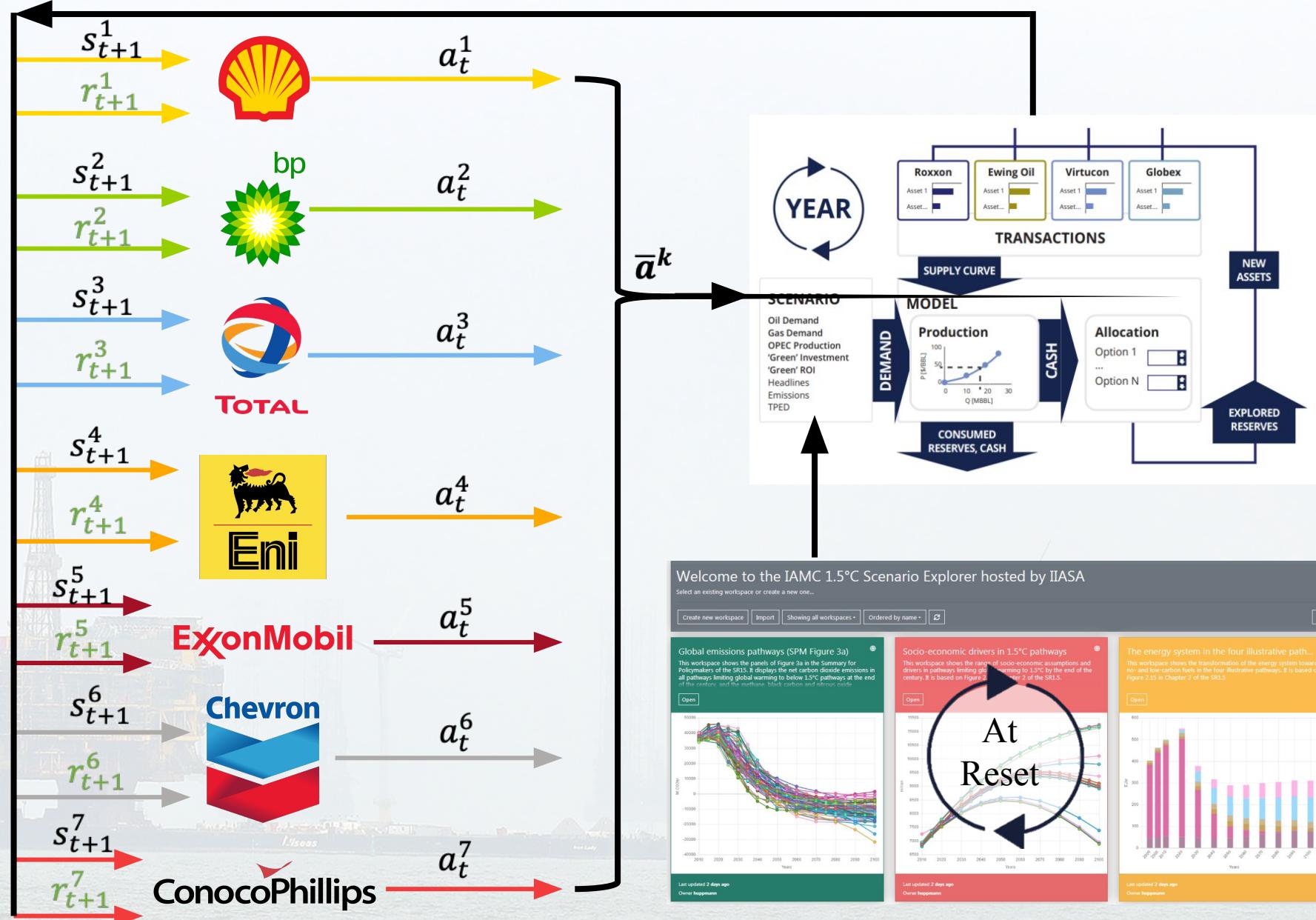
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# Rewards

- Focus on maximizing shareholder value through dividends
- Negative rewards to enforce realistic behavior



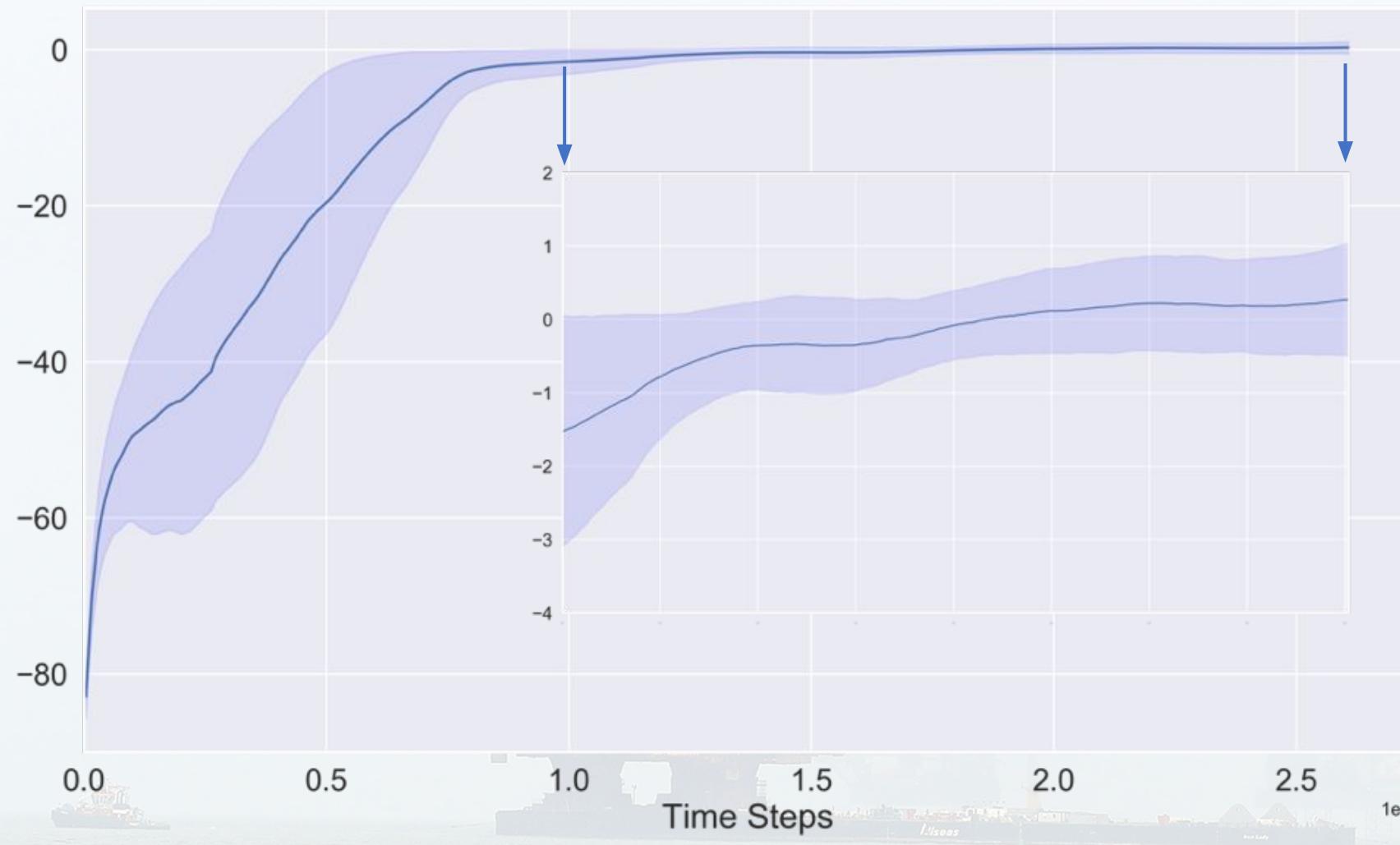
Company: 0 Shell		Assets On Hand (post-all)		Pipeline Assets (Final All)												Pipeline Assets (Begin Dev)				Pipeline Assets (Begin Exp)							
year		Cash(\$)	Debt(\$)	Undl	Undm	Undh	DevL	DevM	DevH	p_Undl	p_Undm	p_Undh	p_DevL	p_DevM	p_DevH	p_Undl	p_Undm	p_Undh	p_DevL	p_DevM	p_DevH	p_Undl	p_Undm	p_Undh			
2019	1062871	689596	0	0	0	0	0	0	0	205	410	615	0	0	0	205	410	615	410	820	1230	1659	13373	2489			
2020	1339661	1447823	0	0	0	0	0	0	0	205	410	615	410	820	1230	829	1659	2489	615	1230	1845	684	1368	2052			
2021	4538608	4999545	0	0	0	0	410	820	1230	829	1659	2489	615	1230	1845	684	1368	2052	820	1640	2460	2317	4635	6953			
2022	1737306	18277687	0	0	0	0	615	1230	1845	684	1368	2052	820	1640	2460	2317	4635	6953	1649	3299	4949	8850	17700	26550			
2023	6279971	66527304	0	0	0	0	820	1640	2460	2317	4635	6953	1649	3299	4949	8850	17700	26550	2333	4667	7001	32069	64139	96208			
2024	22272359	237279488	0	0	0	0	1649	3299	4949	8850	17700	26550	2333	4667	7001	32069	64139	96208	4651	9303	13954	2273474	37080	40505			
2025	83721013	837134545	0	0	0	0	0	2314	4667	7001	32069	64139	96208	4651	9303	13954	113737	2273474	37080	40505	399950	799916	1199874				
2026	202706807	2026156157	0	0	0	0	0	0	0	13501	27003	4667	7001	32069	64139	96208	399950	799916	1199874	113737	2273474	37080	40505	113737	2273474	37080	40505
2027	3310765831	35539445560	0	0	0	0	0	0	0	45571	109748	183220	397321	270462	4191963	193802	18657	477925	486307	671082	7057801	113737	2273474	37080	40505		
2028	111065896960	123546598565	0	0	0	0	0	0	0	182988	42836	66151	486307	971651	14589293	552962	10720801	1956586	3131867	3131867	58697674	58705684	11752369	17682054			
2029	339881755949	42938477488	0	0	0	0	0	0	0	720347	1546899	2338956	16969933	3813867	50720801	1956588	313176	313176	58697674	58705684	11752369	17682054					
2030	138961139727	140929337007	0	0	0	0	0	0	0	2065935	17521369	26782054	6819686	1363971	20459057	17521369	26782054	6819686	1363971	20459057	17521369	26782054	113737	2273474	37080	40505	
2031	4829057132072	5185547632562	0	0	0	0	0	0	0	9452821	1909947	28667778	20420576	488461536	62617308	23726619	47453239	71179859	709363679	1419273356	2182910037	73	1492075037	1492075037	73		
2032	1678129049400	170201040190209	0	0	0	0	0	0	0	0	331057556	2866938072	4349273358	2284791034	847867459	170201040190209	170201040190209	847867459	170201040190209	170201040190209	847867459	170201040190209	170201040190209	170201040190209	170201040190209	170201040190209	
2033	5831589492776	6262105793898	0	0	0	0	0	0	0	0	115622946	231527296	37305952	24665037518	4932075718	7309112556	286693072	38695621545	17139248907	25078873360	996329751	199265903	2989880255	2977910046	59559820093	8933970140	
2034	20265091626217	20265091626217	0	0	0	0	0	0	0	0	4022917	2797572946	419673802	29779910046	59559820093	8933970140	3462367270	6924735451	10387101812	103468761082	206973522164	310460283246	10231991724	24063983468	36095957172	359621912671	
2035	7022192760703	756211431179929	0	0	0	0	0	0	0	0	1398601771	2797572946	419673802	29779910046	59559820093	8933970140	3462367270	6924735451	10387101812	103468761082	206973522164	310460283246	10231991724	24063983468	36095957172	359621912671	
2036	850417843959189	913200345671972	0	0	0	0	0	0	0	0	1688921	2166	3378629937	45796545021	1078865738014	4181901771	359621925363	121947984913631	2499498627262	3749114740893	1424789719461	8342789719461	145298662853	295973275765	435895988595	4342789719461	
2037	29525465212503272	317341772246171874	0	0	0	0	0	0	0	0	58740797037	117410084479	1761156325	2499498627262	3749114740893	145298662853	295973275765	435895988595	4342789719461	8342789719461	145298662853	295973275765	435895988595	4342789719461	151094151094		
Game Info		Policies												Spending Habits													
year		O_Pri	Brw	P_Div	P_Debt	Upl	M	Upl_H	Exp_P	Ex2	Div(\$)	Dbt(\$)	Dev_L(\$)	Dev_M(\$)	Dev_H(\$)	Exp(\$)	I(\$)	TEV(\$)	ROI%	ROE%	D/E%	R/P	Cost of Capital (%)				
2019	34.0	26	33.04	31.74	4.7	9.4	14	89	1390	2314	351209	37390	800176	3530542	5152	83	15	16.34	2.27	0.053	1	1					
2020	14.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	78328	249827	1025	5125	12300	61570	400177	703285	14	0	67.31	0.0	0.004	1				
2021	14.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	23264	486386	1025	5125	12300	208593	1311694	238643.65	0	0	67.33	0.0	0.004	1				
2022	14.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	099812	3231925	4148	9785	79651	5012930	9908121.71	110	0	66.77	13.84	0.003	1					
2023	14.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	329681	11711260	3420	14074	2886267	23739950	110	0	66.86	24.29	0.003	1						
2024	14.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	11588	57942	139062	10236351	63672123	116923716.66	110	0	66.99	58.59	0.004	1						
2025	14.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	41116360	146857638	42458	221256	531010	35996247	223966754	411163608.07	110	0	67.06	98.98	0.094	1				
2026	14.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	163848	801741	1924178	125758917	827568857	143646897.78	110	0	67.11	242.62	0.094	1						
2027	6.71	51	52.5	18.65	25.0	21.16	25.35	4.6	100	499934307	1775916149	568686	2843430	662423	43767892	273736587	4999583478.96	31	0	67.14	541.04	0.094	1				
2028	29.3	51	52.5	18.65	25.0	21.16	25.35	4.6	100	6040693426	2145835275	69866	34393823	83839729	5288461633	32913266554	6047243871.21	0	0	67.15	188.89	0.094	1				
2029	9.6	51	52.5	18.65	25.0	21.16	25.35	4.6	100	730283	745700	21451454	19218722	1431564864	1878301454	180955959859.09	0	0	67.16	228.72	0.094	1					
2030	2.4	51	52.5	18.65	25.0	21.16	25.35	4.6	100	730283	745700	21451454	19218722	1431564864	1878301454	180955959859.09	0	0	67.16	228.72	0.094	1					
2031	0.6	51	52.5	18.65	25.0	21.16	25.35	4.6	100	36995712040030	1313274939106	4284812265	21240611339	514177467213	3235957214042	202134451890801	36976953113427.25	0	0	67.16	4019375.53	0.094	1				
2032	0.2	51	52.5	18.65	25.0	21.16	25.35	4.6	100	512532541904	90052856183	23928142	1469017210	3235641008	2120313765687	13812073399133	2535617313939.83	0	0	67.16	175588.95	0.094	1				
2033	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	1063860539743	1379151233	12303187593	61659537968	17496251124	931380847397	5796587505542	10640690054725.27	0	0	67.16	11565572.19	0.094	1				
2034	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	1060600	388000	246000	541200	1072128841	1510514207	1272346897	71716200820	48000807505426	88113032136.22	0	0	67.16	11565572.19	0.094	1		
2035	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	379462.25	2146467.66	379462.25	494925.37	1088833	1567901.9	700161.0	1450354	10630916745.23	16688071321105	16688071321105	0	0	67.16	139666219.72	0.094	1	
2036	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	5151422403508	551117246443562	179810563357	899057816789	21577341762095	1358227851321757	845313510267470	1.551726517989572e+16	0	0	67.16	1686608279.81	0.094	1				
2037	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	21897.94	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0		
2038	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	21897.94	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0		
2039	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	21897.94	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0		
2040	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	21897.94	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0		
2041	0.0	51	52.5	18.65	25.0	21.16	25.35	4.6	100	21897.94	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0		
2042	0.0	51	52.5	18.65	25.0	21.16	25.35																				

## Reason for Negative Rewards:

Intelligent agents love to  
find loopholes!

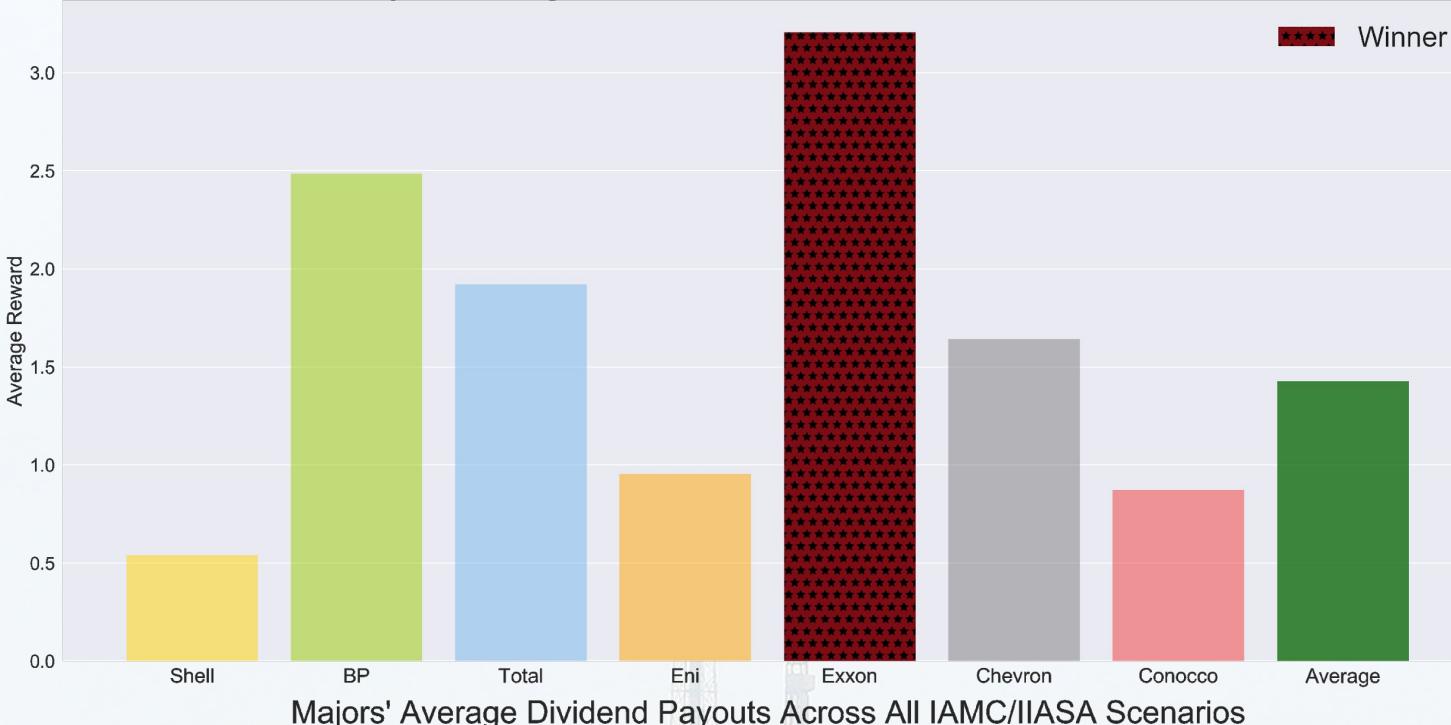
# Results & Analysis



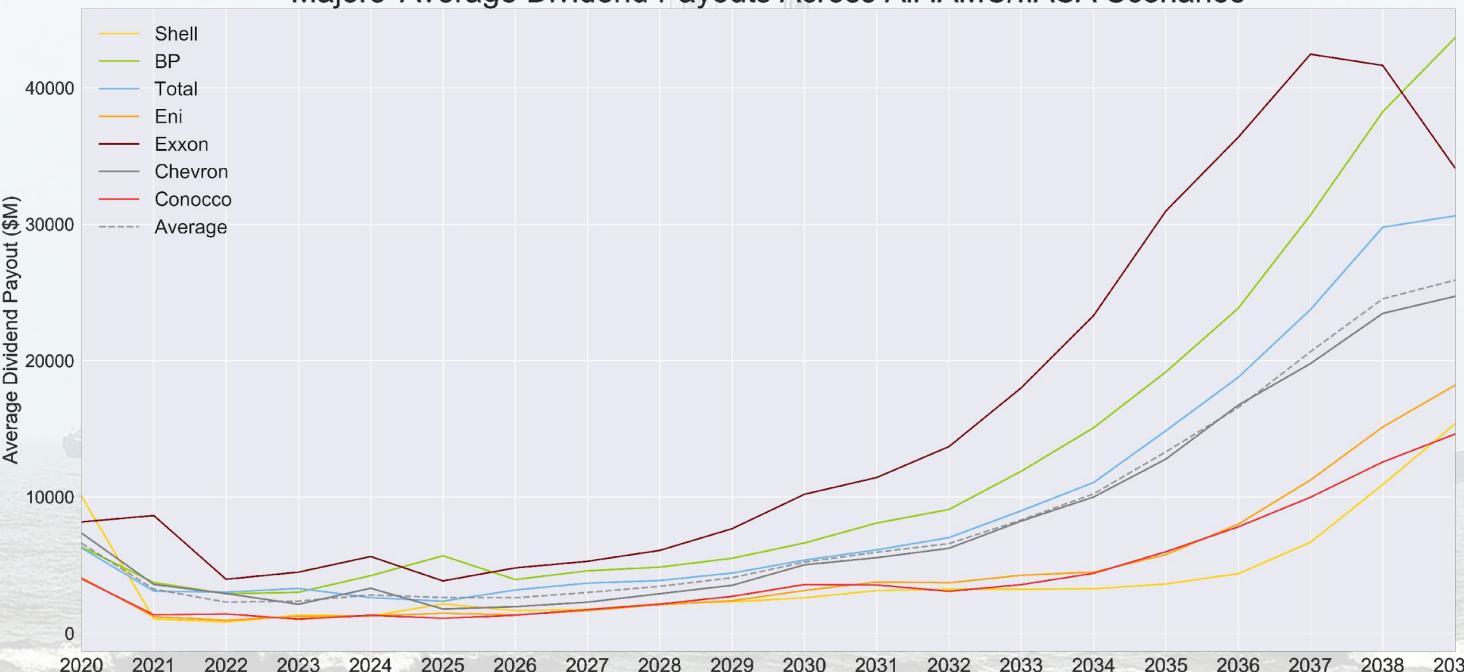


- Convergence towards a scenario-robust solution is reached after  $\sim 2.6M$  timesteps, or 320 pass throughs each scenario ( $\sim 130,000$  games played)
- Convergence towards a positive reward indicates agents achieved realistic, robust strategies to maximize dividend payouts
- Oil and gas, 'green' and debt holdings are explored to evaluate the Majors' business models

## Majors' Average Reward Across All IAMC/IIASA Scenarios

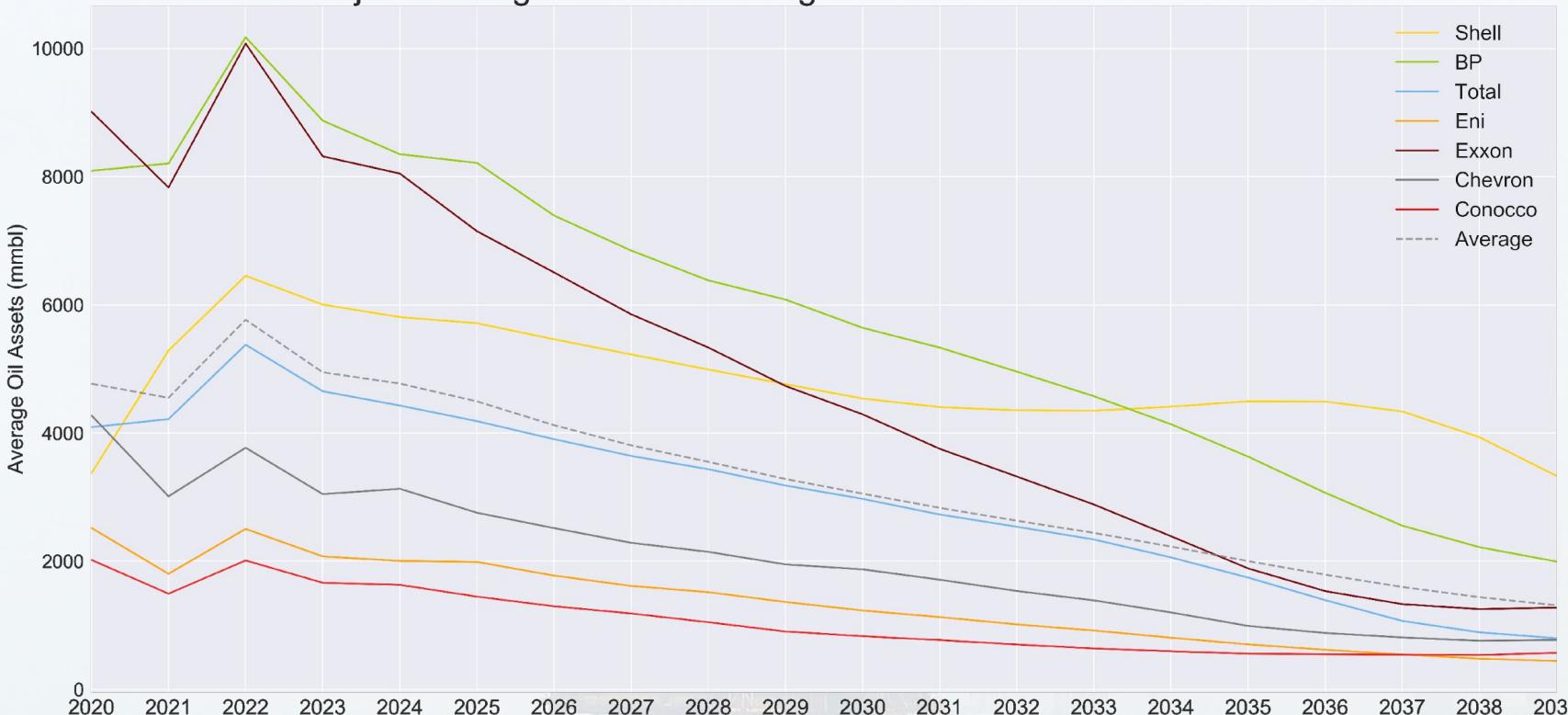


## Majors' Average Dividend Payouts Across All IAMC/IIASA Scenarios



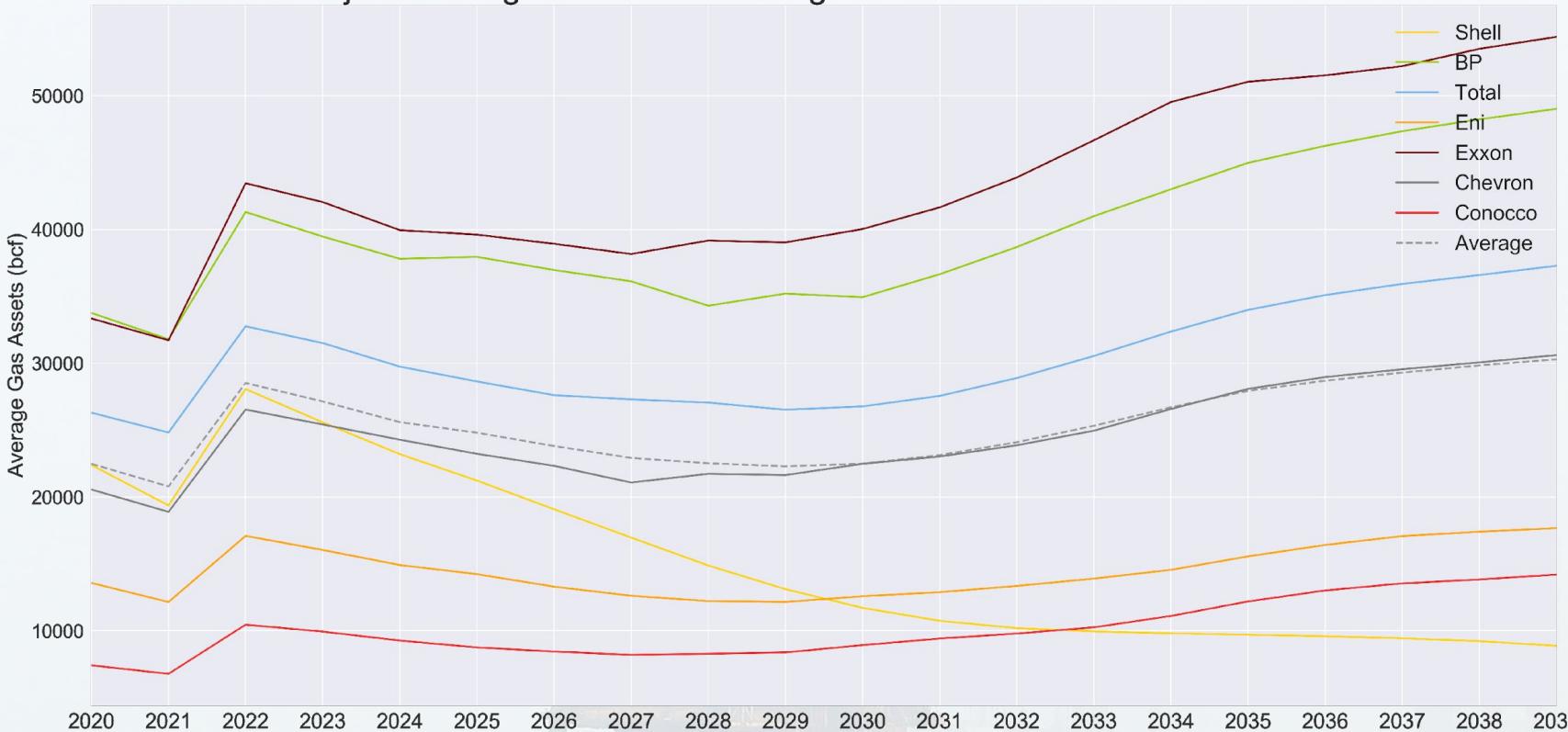
- Across all scenarios, Exxon pays out the most dividends while maintaining a realistic strategy pathway
- Average yearly dividend payouts take an initial dip before noticeably increasing in the latter half of the game

### Majors' Average Oil Asset Holdings Across All IAMC/IIASA Scenarios



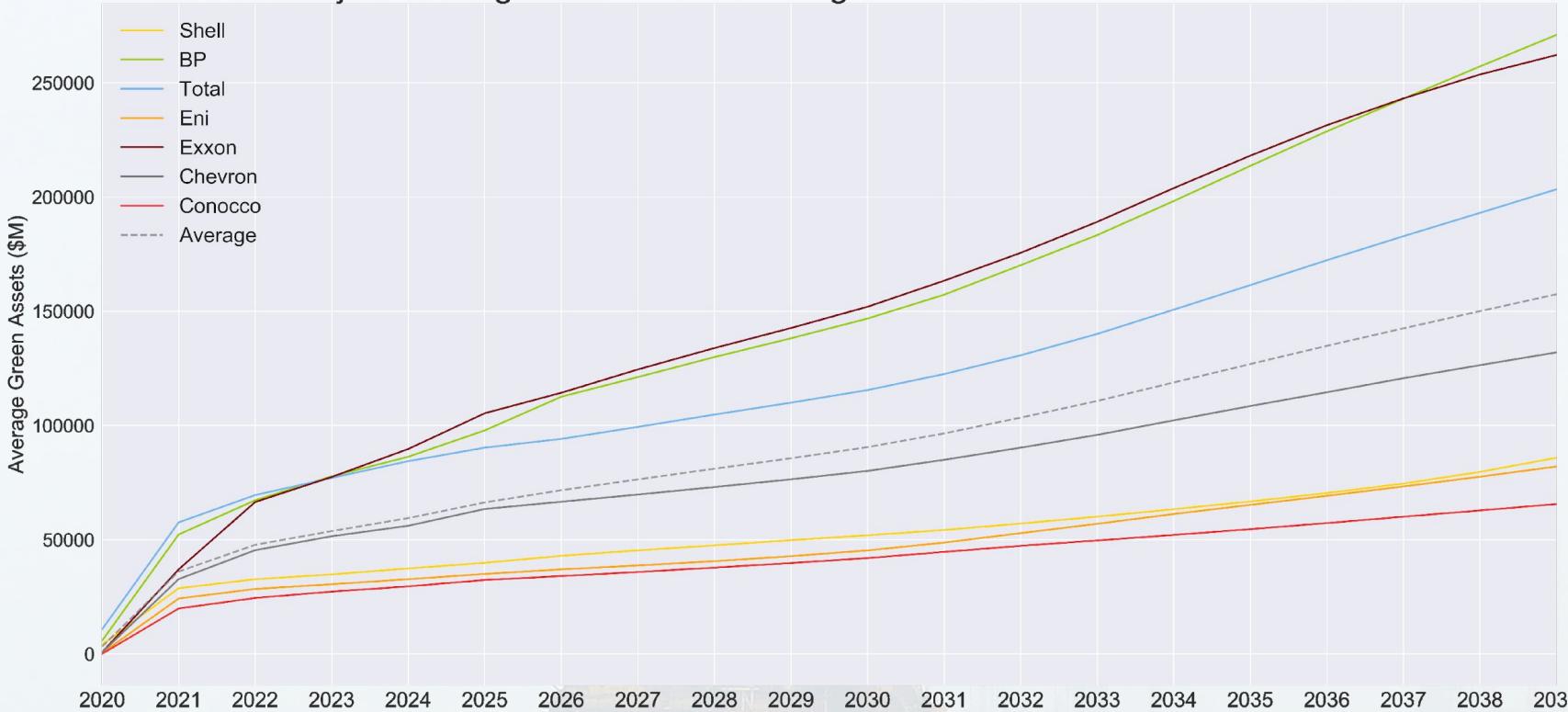
- Majors heavily divest from oil assets early, continue divestment throughout
- Shell and BP maintain the greatest oil market share at the end game

### Majors' Average Gas Asset Holdings Across All IAMC/IIASA Scenarios



- Majors gradually increase gas asset holdings, suggesting the carbon asset's net income stability
- Gas market shares remain similar, however, Shell tends to let its market share slip

## Majors' Average Green Asset Holdings Across All IAMC/IIASA Scenarios



- Majors heavily invest in 'green' assets; display similar 'first-mover' behavior and long-term trends
- Exxon and BP act as leaders of the 'green' movement primarily due to their large, initial balance sheets

## Majors' Average Debt Holdings Across All IAMC/IIASA Scenarios



- Hints of a leverage transition (i.e. borrowing cash to buy 'green' assets) undertaken by BP and Total, Exxon and Chevron.
- Levels of debt increase towards the end game due to Majors' new debt resilience

# Impact



## **Moving First, Benefits Outweigh Costs**

Moving first into 'green' assets allows Majors to accumulate higher returns long-term and maintain stable levels of debt



## **Decarbonization of Emission Leaders**

Providing a financial case for the decarbonization of the Oil Majors helps stakeholders understand the potential these carbon emission leaders have to become net-zero vanguards

## **A Robust, 'Green' Strategy**

Going 'green' while diminishing net income reliance on oil assets proves a robust response to uncertainty in a 1.5C world

# Future Work





Capital cost  
sensitivity  
analysis

Modeling  
National  
Oil Companies



Expanding  
'green' asset  
allocation

Focus on corporate  
governance  
questions



Mass rollout  
as 1-player  
game

# Thank You!



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