Profitability of a Two-Product Biorefinery

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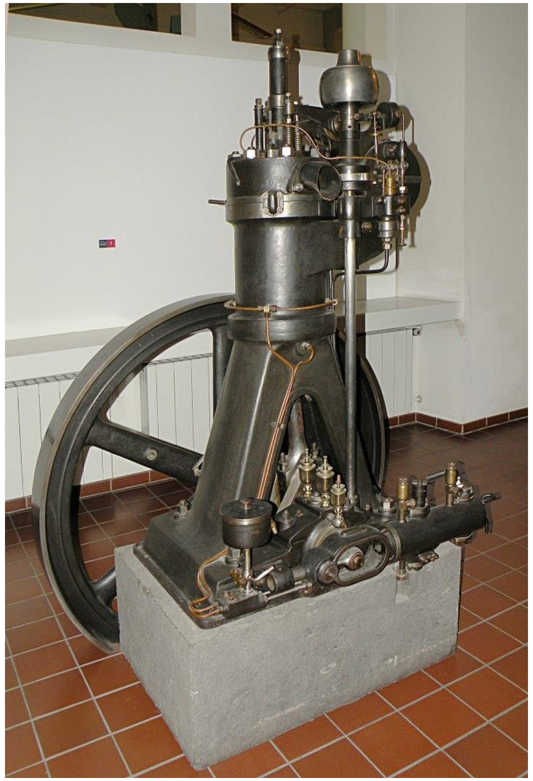
Conversion of biomass to energy products is not new

- By 1900, a fully operational biodiesel engine was on display at the World's Fair.
- During WW2, biodiesel served as a gap motor fuel and even as engine fuel for combat airplanes and tanks.
- Some biofuels such as corn, soybeans, and sugarcane do support substantial scale economies for ethanol or Dimethyl ether (not but at scales of fossil fuels).



Rudolf Diesel invented the diesel engine, unveiled at 1900 World's Fair. Ran on peanut butter oil.

Why cotton?

- Cotton gin waste (CGW) is produced in abundance at cotton gins across Texas and usually left unutilized. During harvest season, piles of cotton gin waste can be found at gins throughout the state.
- CGW contains a significant amount of cellulose.
- LePori et al. (1982): CGW collected at gin could supply the entire energy needed in stripper harvesting areas.
- Lacewell et al. (1982): one ton of CGW potentially contains 14 million Btus of energy (= 120 gallons of gasoline).

Why cotton?

- The feedstock (cotton -> cotton gin waste) is already shipped to the gin.
- Peaking power electricity is high during the winter ginning season, so any excess biopower adds value streams to gin cooperatives.
- Biopower production is partly counter-cyclical to weather risks:
  - ➢During bumper crops all excess gin trash used to avoid beetle infestation
  - ➢During droughts, all the gin trash is applied to the highest valued products - peak electric prices, and if prices eventually allow, ammonia fertilizer.

Cotton Gin ‘Trash’ Finding New Life In The Form Of Electrical Power – Texas A&M Today

“The fluidized bed gasification system was developed in the 1980s when a patent was issued to Drs. Calvin Parnell Jr. and W.A. Lepori, who were both part of the Texas Agricultural Experiment Station now Texas A&M AgriLife Research.”

“The process is gasification,” [Dr. Sergio] Capareda said. “We limit the amount of air to thermally convert the biomass so the products are combustible gases. These are collectively called synthesis gas. Carbon monoxide and hydrogen, plus a little methane, ethlyene, these are a combustible mixture. Combustible in a sense that you can feed it into an internal combustible engine coupled with a generator so you can turn this fuel into electrical power.”

Source: [Link]

Image source: [Link]

Too few data points

- *Annual* cotton gin waste data
- *Monthly* ammonia price data
- *Hourly* electricity price data
- How can we run an optimization model with (i) too few data points (cotton gin waste) and (ii) inconsistent data frequency/granularity?

Bayesian simulation - 10,000 data points simulated from real data

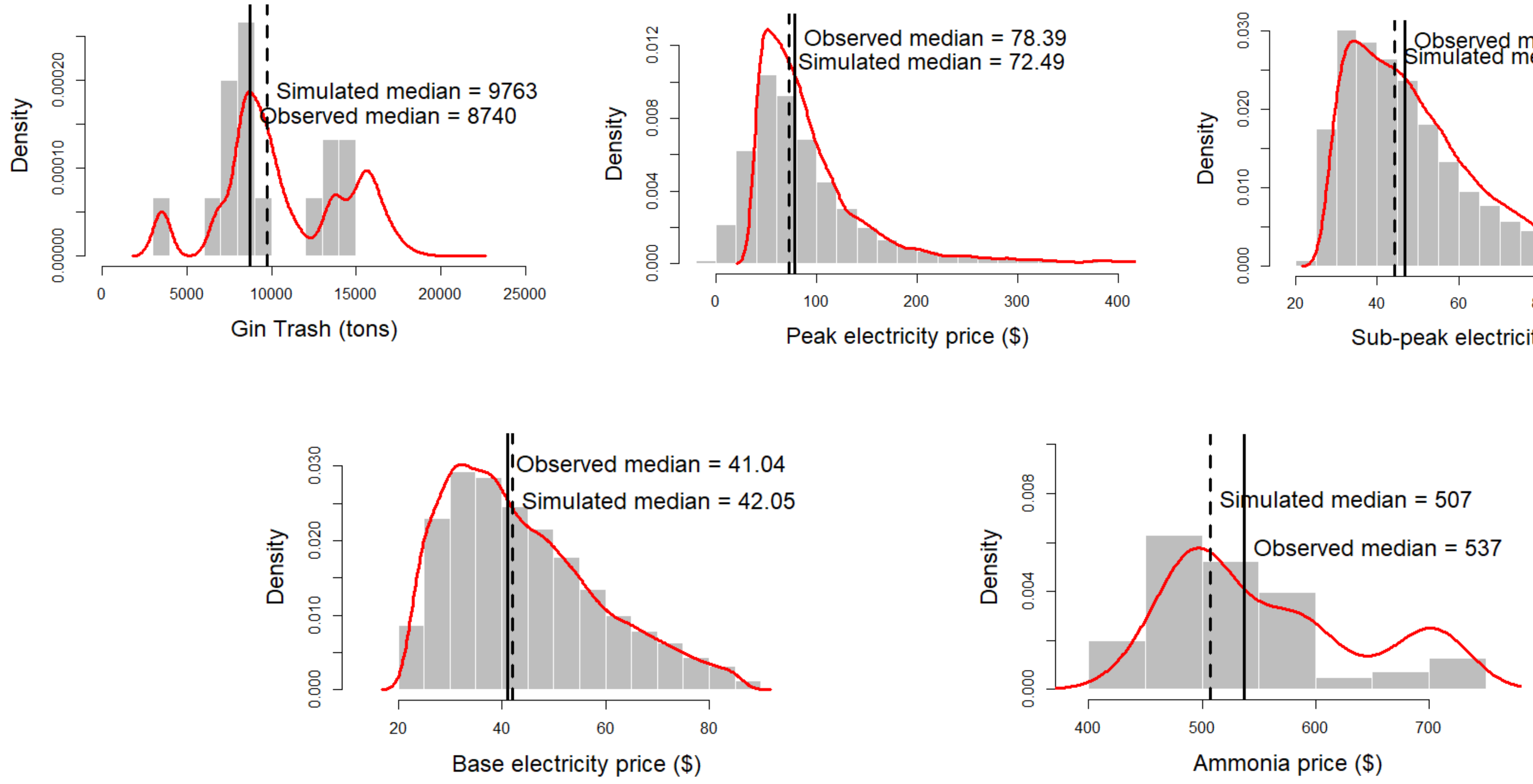
$$Y = \beta X + \epsilon$$

- Uses Gibbs sampling to estimate the posterior distribution of the model coefficients (β) and error variance (σ^2). (Preserves data quirks without resampling.)
- How does it work? Iteratively draw samples from conditional distributions of both parameters:
    1. Set a specified number of iterations for the Gibbs sample (11,000) and a burn-in sample (1,000).
    2. Enter a loop where in each iteration, β and σ^2 parameters are alternately updated.
    3. For β, a sample is drawn from a multivariate normal distribution based on the covariance matrix and mean values parameters.
    4. The mean and covariance matrix for this distribution are calculated based on the current values of the data and a σ starting value of 0.50.
    5. σ is subsequently updated by drawing a sample (inverse transformation sampling) from inverse gamma distribution, and the updated σ is used in the next iteration of drawing β.
    6. The loop continues until 10,000 samples are drawn after discarding the burn-in samples.
    7. Finally, new values of the dependent variable are simulated using the sampled β coefficients.

Data – 10,000 data points simulated from real data

- Annual cotton gin waste data over 15 years collected from Ropes Farmer Co-op Gin
    - ➢Simulated from precipitation data (includes two of top five 2-yr records for drought and one of the three highest 2 years rainfall events since 1908)
- Monthly anhydrous ammonia price from DTN Progressive Farmer database
    - ➢Simulated from price of major crops and oil (corn, cotton, oats prices and lagged oil price)
- Hourly electricity price from ERCOT over 12 years
    - ➢Simulated from temperature

Simulated data very close to observed data



Optimization

Revenue: $P_pE_p + P_{SP}E_{SP} + P_BE_B + P_MM + 10 * GW_f$

Marginal cost: $5.5\left(E_p + E_{SP} + E_B + E_M\right) + 130.34 * M$

Fixed cost: $37645 * ME + 0.100385 * \left[640000 + \frac{4000000}{1.2*C+5}\right] * C$

MAX Revenue $[P_pE_p + P_{SP}E_{SP} + P_BE_B + P_M\frac{E_M}{11} + 10 * GW_f]$ – Marginal Costs $[5.5\left(E_p + E_{SP} + E_B + E_M\right) + 130.34 * \frac{E_M}{11}]$ – Fixed Costs $[0.100385 * \left[640000 + \frac{4000000}{1.2*C+5}\right] * C - 37645 * ME]$

Optimization

$$MAX\ P_p E_p + P_{UB} E_{UB} + P_{LB} E_{LB} + P_M \frac{E_M}{11} + 10 * GW_f - 5.5\left(E_p + E_{UB} + E_{LB} + E_M\right) - 130.34 * \frac{E_M}{11} - 0.100385 * \left[640000 + \frac{4000000}{1.2 * C + 5}\right] * C - 37645 * ME$$

Subject to:

[1] $(E_p + E_{UB} + E_{LB} + E_M + GW_f) \leq$ CGW

[2] $(E_p + E_{UB} + E_{LB} + E_M) \leq$ 5403*C

[3] $0 \leq E_P \leq 1071$

[4] $0 \leq E_{UB} \leq 2432$

[5] $0 \leq E_{LB} \leq 1900$

[6] $0 \leq M \leq 550$

[7] $0 \leq E_M \leq 6050$

Optimization

$$MAX\ P_pE_p + P_{UB}E_{UB} + P_{LB}E_{LB} + P_MM - 5.5\left(E_p + E_{UB} + E_{LB} + E_M\right) - 130.34 * M - 37645 * ME - 0.100385 * \left[640000 + \frac{4000000}{1.2*C+5}\right] * C + 10 * GW_f$$

- P_p is peak electricity price; E_p is the MWe of electricity sold each month at peak prices;
- P_{UB} is sub peak electricity price; E_{UB} is the MWe of electricity sold each month at subpeak prices;
- P_{LB} is the price of base electricity; E_{LB} is the MWe of electricity each month at base prices;
- P_M is the price of ammonia, M; E_M is electricity in MWe required to produce M (11 is needed to produce every ton of ammonia, M);
- ME is the number of ammonia processors, which ranges from 0 to 2;
- C is installed power capacity, which ranges from 1-5 MWe for the small gin and 1-9 MWe for medium gins;
- GW_f is gin waste sold as feed

Illustration: Solving Profit Maximization and Investor Choices

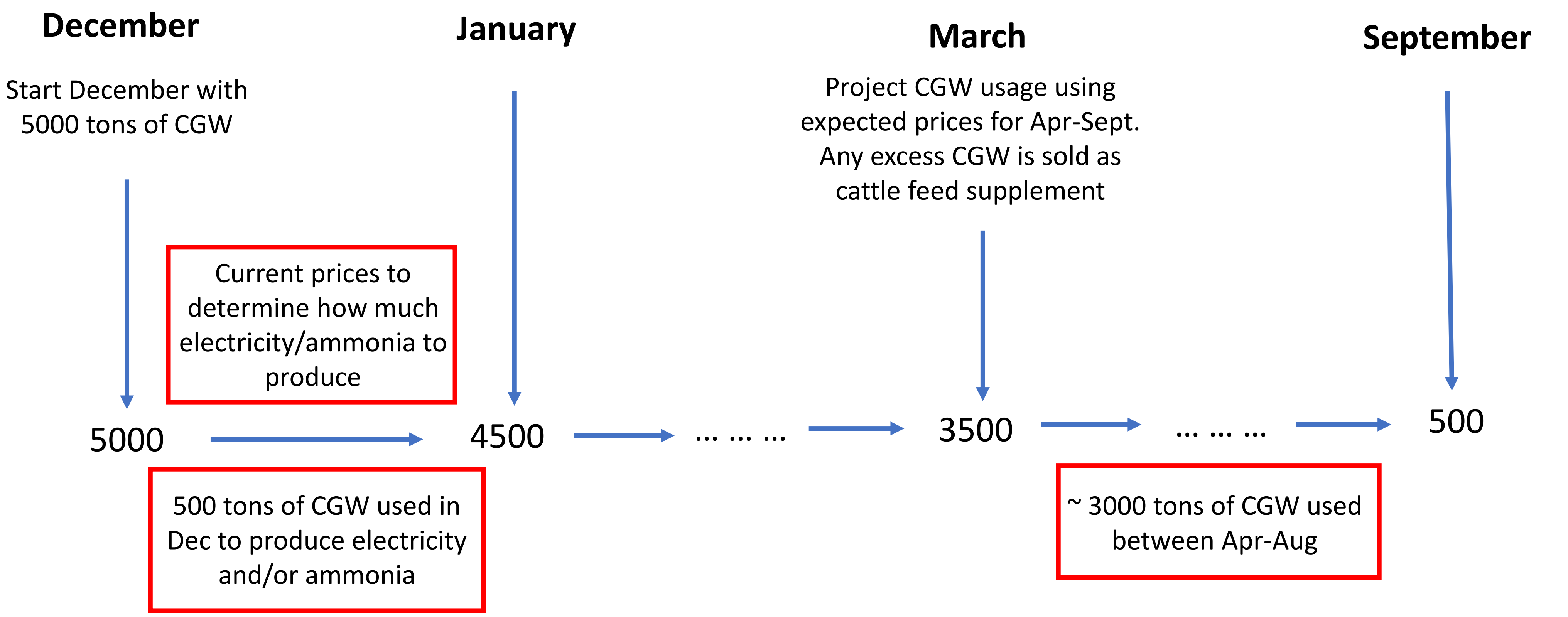
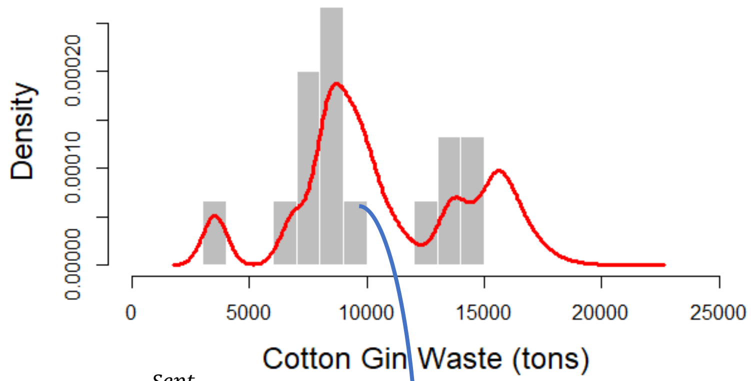


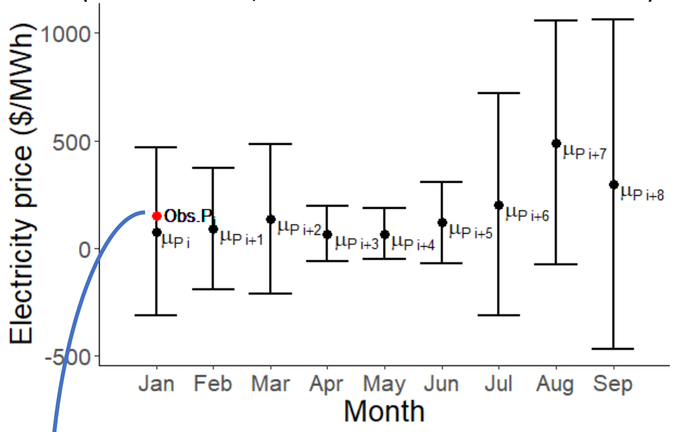
Illustration: Solving Profit Maximization and Investor Choices

Distribution of Expected Annual Total Cotton Gin Waste

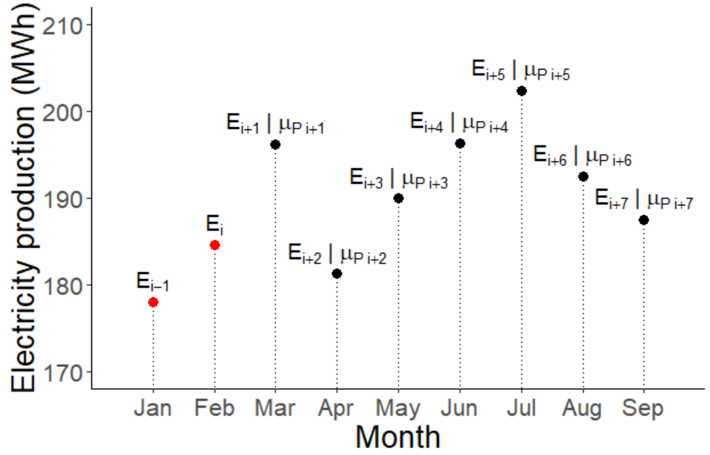


$$\sum_{i=Jan}^{Sept} Monthly\ CGW_{Jan} = Total\ CGW$$

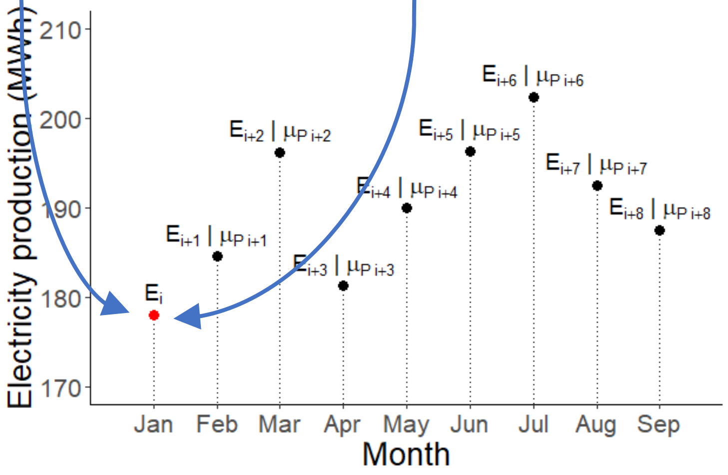
Average Electricity Prices by Month (nine months, mean and standard deviation)



Second Month Choice of Electricity Produced (based on Total CGW − c_{t-1}, Observed Price ($Obs.P_i$), and Expected Monthly Prices (μ_{pi}))



$$Monthly\ CGW_{Feb} = Total\ CGW - CGW_{Jan}$$



First Month Electricity Production (E_i) (based on Total CGW, Observed Price ($Obs.P_i$), and Expected Monthly Prices (μ_{pi}))

$$Max\ Expected\ Revenue = \sum_{i=Jan}^{Sept} (E_i * \mu_{pi})$$

Model is flexible: Key trade-off to optimize

- Trade-off: Do we use all the gin during winter to produce electricity or store some for the summer?
  - ➢Average electricity prices highest in winter
  - ➢Yet, peaking prices are higher in the summer

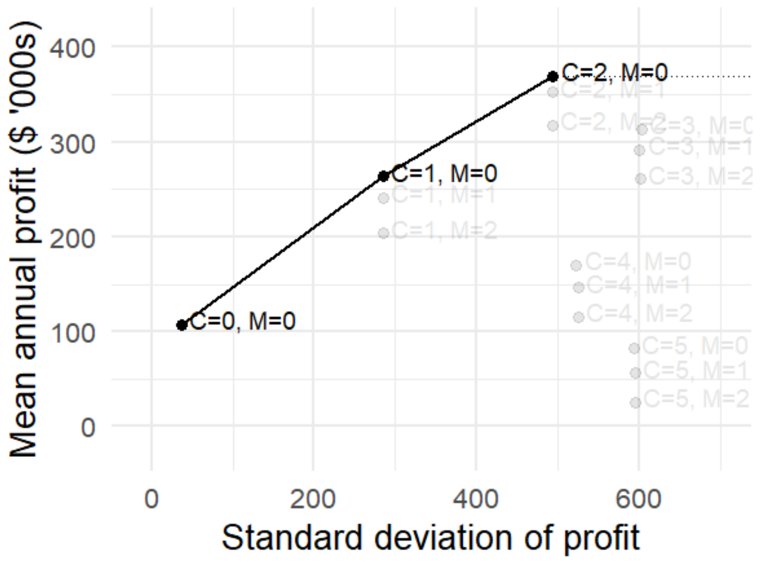
Model is flexible: Key trade-off to optimize

- Model is flexible and allows for month-to-month individualized operational decision-making
  - Once gin trash volume for the season is known, operator will have precise expectations of electric prices for immediate month and reasonable expectations of future month.
  - Also know the schedule of their own electric power demands over the ginning season, them to allocate power to ginning operations and the grid.
  - Has the option to sell gin waste as animal feed supplement in March or hold gin waste to sell peak electricity during summer months. (But risk beetle emergence).

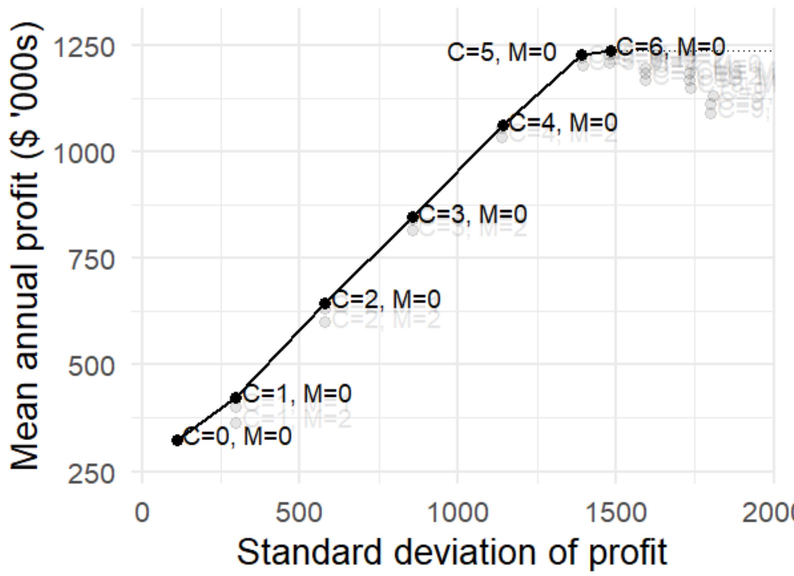
Profitable baseline scenario

EV frontier is almost linear instead of a 'bowed' shape, reflecting in part the operational flexibility in month-to-month decision-making

Small Gin



Medium Gin

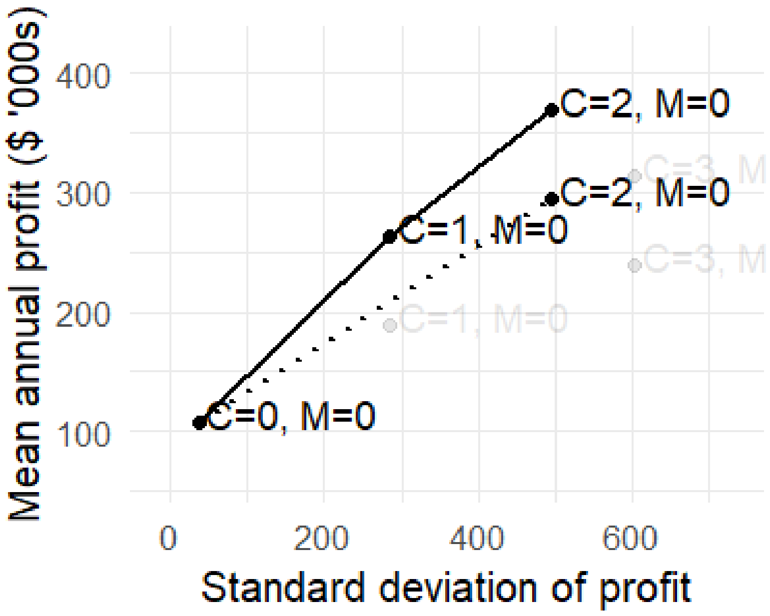


- As plant capacity increases from 1MWe to 2MWe, ROIC falls, prob of loss increases, but avg profit increases.
- Operational choices do change at the larger scale though: less gin waste is sold & more is used to produce electric power production.

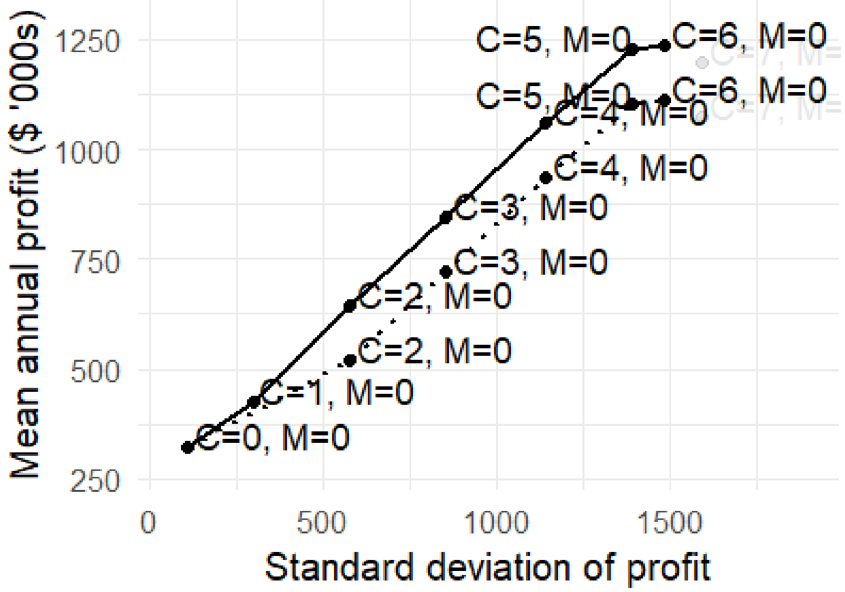
- Beyond 6MW, added electricity generation capacity lowers profits and increases chance of loss.
- No scenario with ammonia processor is on the frontier.
- With ammonia processor, revenues are higher yet do not justify the added investment given alternatives.

Profitable with added fixed cost for operator

Small Gin



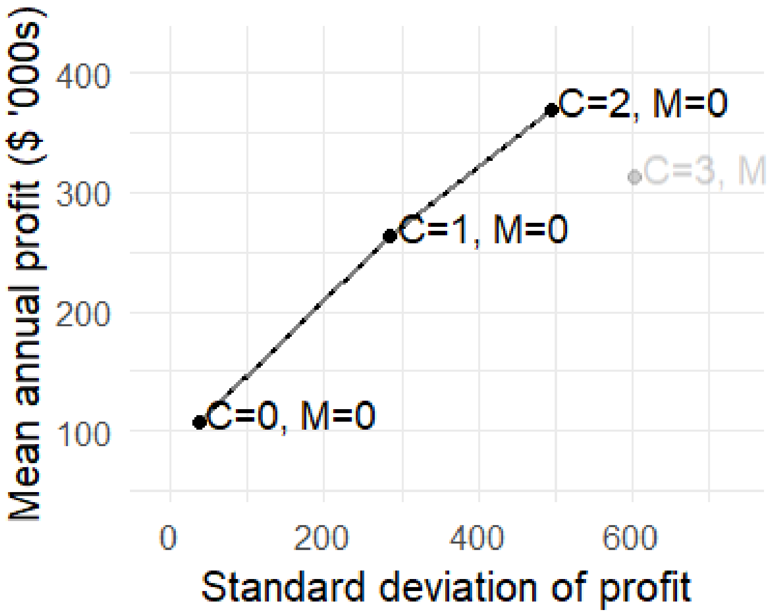
Medium Gin



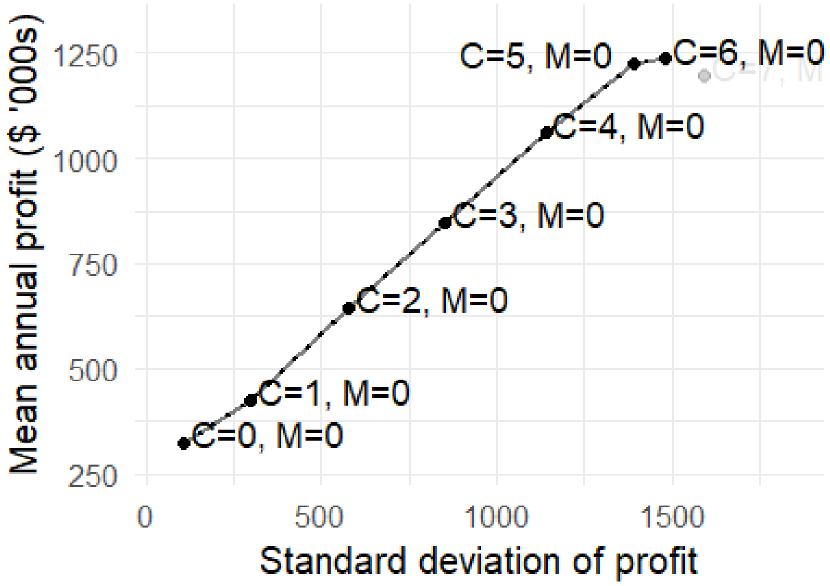
- Reduces 12-year cumulative profits for the 2 MWe plant at the small gin by 20% and for the 6 MWe plant at the medium gin, by 10%.
- No change in plant capacity or output combination.

Profitable with lower base electricity price by 50%

Small Gin



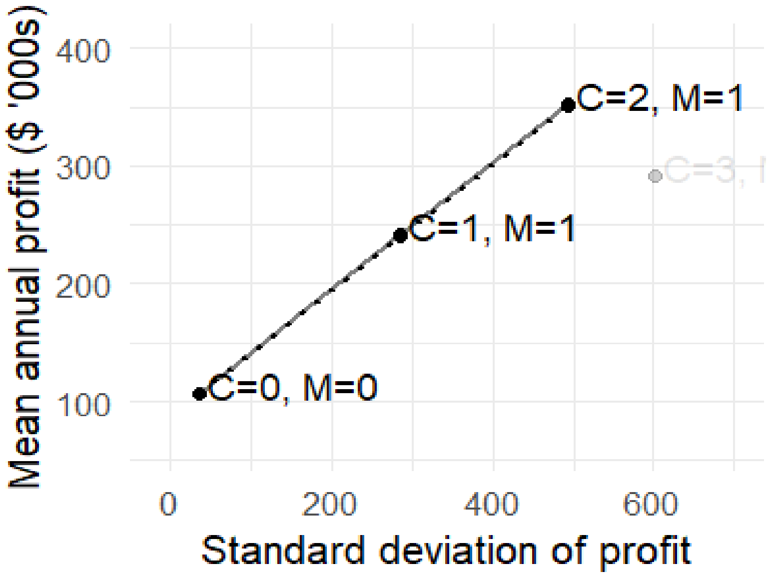
Medium Gin



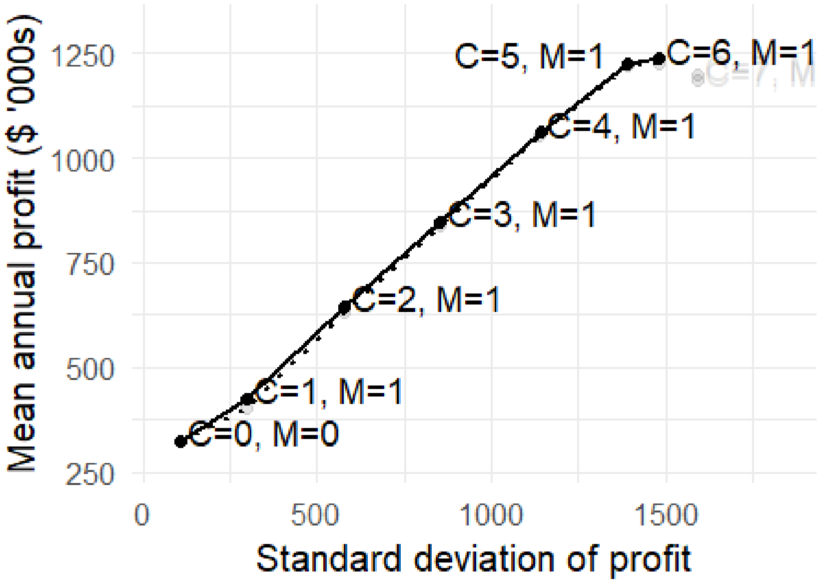
- Plant capacity is unchanged; only marginally reduced profit and ROIC.
- Diverts electric power to ammonia production via electrolysis.
- Small gin w/ C=2 and M=1: electric power sold decreases by 21% & ammonia production rises from 195 tons to 331 tons.

Profitable with lower marginal cost of ammonia by 1/3

Small Gin



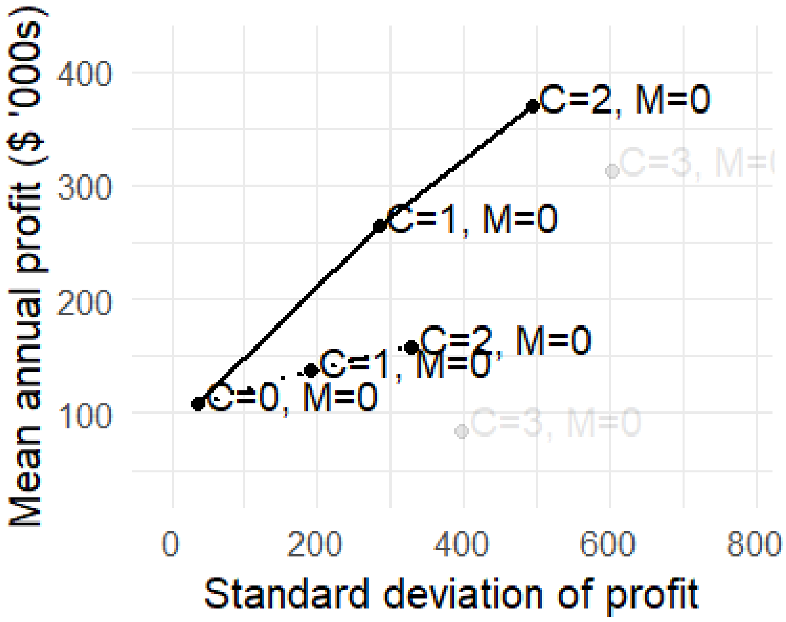
Medium Gin



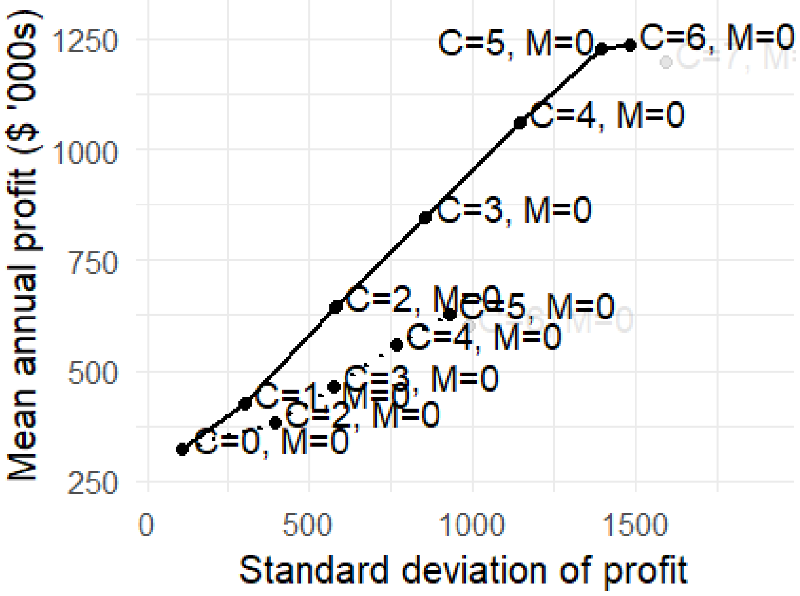
- Does not alter optimal plant composition & plants with no ammonia processor remain more profitable.
- Decreases the amount of electricity *sold*, especially power at base prices, as power generation is diverted to increase ammonia output.

Profitable with lower gin-to-electricity conversion rate of 1/3

Small Gin



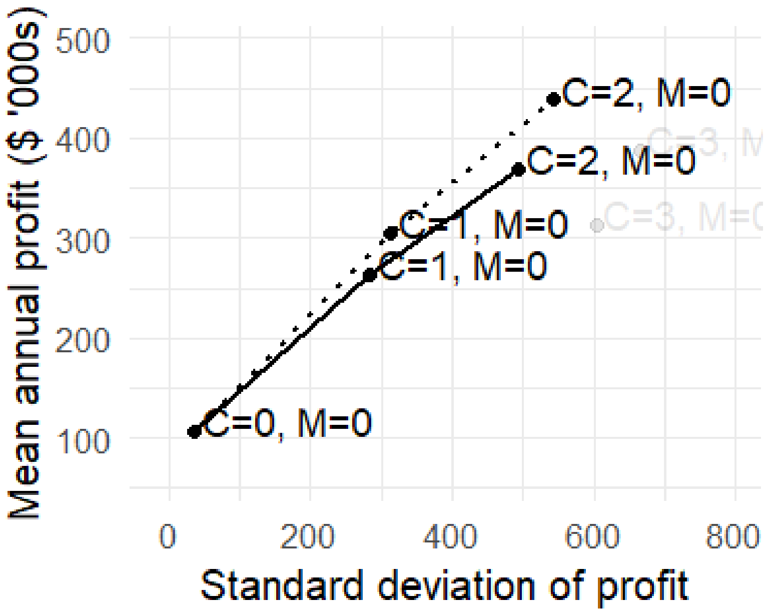
Medium Gin



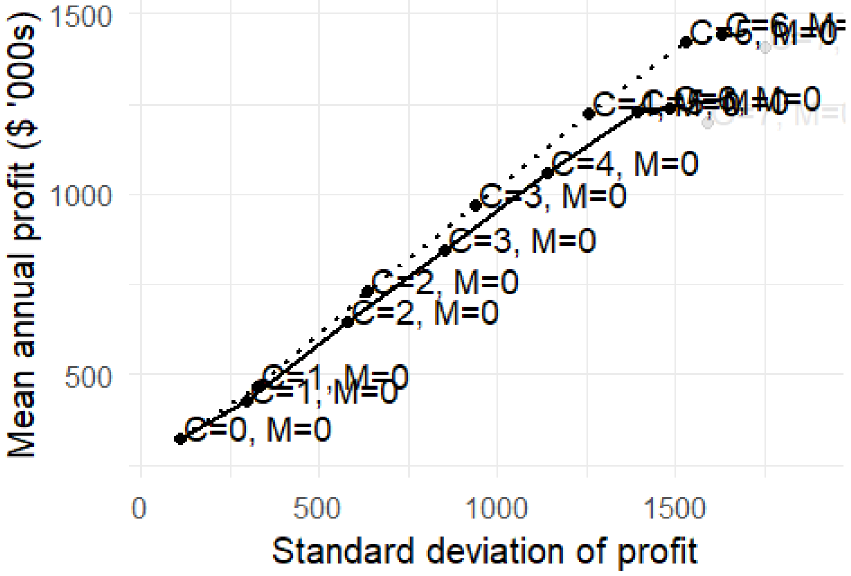
- 12-year cumulative profits fall by 57% (small gin) & 49% (medium gin).
- Optimal plant size now reduces from 6 MWe to 5 MWe.
- CGW management changes very little, with a bit more CGW sold in March for a bit less power generation in summer.

Profitable with 10% higher electricity prices

Small Gin



Medium Gin



- No change in the optimal plant composition, output combination or shape of EV frontier.
- Predictably, the average profit, cumulative profit and ROIC increase.

Profitability on the frontier

Profitability on the frontier - Small Gin

Models	Avg. ROIC	Prob. loss	Prob. ROIC > 100	Avg. profit	SD profit
C=0, M=0 ^{EV,*}	0.00	0.00	0.00	107,516	36,626
C=1, M=0 ^{EV}	82.17	0.29	17.26	264,011	284,846
C=2, M=0 ^{EV}	64.29	6.19	12.83	369,700	494,065

Profitability on the frontier - Medium Gin

Models	Avg. ROIC	Prob. loss	Prob. ROIC > 100	Avg. profit	SD profit
C=0, M=0 ^{EV,*}	0.00	0.00	0.00	322,549	109,878
C=1, M=0 ^{EV}	132.13	0.00	57.66	424,517	297,249
C=2, M=0 ^{EV}	112.01	0.00	31.23	644,104	577,942
C=3, M=0 ^{EV}	104.69	0.01	25.79	846,254	854,539
C=4, M=0 ^{EV}	103.31	1.04	25.02	1,061,195	1,140,497
C=5, M=0 ^{EV}	98.96	3.54	23.35	1,227,070	1,391,770
C=6, M=0 ^{EV}	85.76	5.10	19.02	1,237,195	1,482,193

12-yr cumulative profitability on the frontier

Cumulative profitability on the frontier - Small Gin

Models	Disc. Avg. profit 12 yrs.	SD disc. profit 12 yrs.	Disc. Avg. ROIC 12 yrs.	Prob. ROIC < 0	Prob. ROIC between 0 & 250	Prob. ROIC between 250 & 500	Prob. ROIC > 500
C=0, M=0 ^{EV,*}	484,920	44,933	0.00	0.00	0.00	0.00	0.00
C=1, M=0 ^{EV}	1,190,743	366,304	370.61	0.00	12.00	74.31	13.69
C=2, M=0 ^{EV}	1,667,423	632,674	289.95	0.00	44.66	50.66	4.68

Cumulative profitability on the frontier - Medium Gin

Models	Disc. Avg. profit 12 yrs.	SD disc. profit 12 yrs.	Disc. Avg. ROIC 12 yrs.	Prob. ROIC < 0	Prob. ROIC between 0 & 250	Prob. ROIC between 250 & 500	Prob. ROIC > 500
C=0, M=0 ^{EV,*}	1,454,760	134,800	0.00	0.00	0.00	0.00	0.00
C=1, M=0 ^{EV}	1,914,656	377,991	595.93	0.00	0.00	24.13	75.87
C=2, M=0 ^{EV}	2,905,040	741,192	505.17	0.00	0.00	55.58	44.42
C=3, M=0 ^{EV}	3,816,778	1,098,925	472.15	0.00	0.00	63.99	36.01
C=4, M=0 ^{EV}	4,786,208	1,473,196	465.97	0.00	0.60	64.71	34.69
C=5, M=0 ^{EV}	5,534,335	1,813,371	446.31	0.00	2.28	66.99	30.73
C=6, M=0 ^{EV}	5,580,001	1,898,134	386.78	0.00	10.56	70.83	18.61

Extended analysis – small gin

Models[a]	Avg. ROIC	Prob. loss	Prob. ROIC > 100	Avg. profit	SD profit
C=0, M=0 EV, *	0.00	0.00	0.00	107,516	36,626
C=1, M=0 EV	82.17	0.29	17.26	264,011	284,846
C=2, M=0 EV	**64.29**	**6.19**	**12.83**	**369,700**	**494,065**
C=3, M=0	38.78	14.11	7.04	313,519	602,822
C=4, M=0	16.58	35.30	2.39	170,302	523,131
C=1, M=1	59.08	2.11	11.27	241,505	284,887
C=2, M=1	53.18	6.75	10.38	352,330	493,492
C=3, M=1	32.58	17.99	5.86	291,900	600,695
C=4, M=1	13.17	40.64	1.92	146,800	524,745
C=1, M=2	41.08	4.96	8.06	203,860	284,887
C=2, M=2	42.40	8.12	7.94	317,992	493,718
C=3, M=2	26.56	25.85	4.91	261,189	602,075
C=4, M=2	9.64	46.91	1.62	115,922	525,505

Extended analysis – small gin

Models	Disc. Avg. profit 12 yrs.	SD disc. profit 12 yrs.	Disc. Avg. ROIC 12 yrs.	Prob. ROIC < 0	Prob. ROIC between 0 & 250	Prob. ROIC between 250 & 500	Prob. ROIC > 500
C=0, M=0 [EV, *]	484,920	44,933	0.00	0.00	0.00	0.00	0.00
C=1, M=0 [EV]	1,190,743	366,304	370.61	0.00	12.00	74.31	13.69
C=2, M=0 [EV]	**1,667,423**	**632,674**	**289.95**	**0.00**	**44.66**	**50.66**	**4.68**
C=3, M=0	1,414,036	765,230	174.92	0.00	81.75	17.29	0.96
C=4, M=0	768,095	652,694	74.78	1.80	95.80	2.40	0.00
C=1, M=1	1,089,237	366,113	266.45	0.00	51.50	47.18	1.32
C=2, M=1	1,589,080	630,754	239.84	0.00	62.91	35.41	1.68
C=3, M=1	1,316,530	762,939	146.95	0.12	88.12	11.16	0.60
C=4, M=1	662,097	654,167	59.40	5.76	92.56	1.68	0.00
C=1, M=2	919,451	366,108	185.26	0.00	81.87	17.89	0.24
C=2, M=2	1,434,208	630,886	191.21	0.00	78.03	21.73	0.24
C=3, M=2	1,178,016	764,319	119.79	0.12	93.40	6.36	0.12
C=4, M=2	522,831	654,923	43.49	13.57	85.11	1.32	0.00

Extended analysis – small gin

Models	Avg. ROIC	Prob. loss	Prob. ROIC > 100	Avg. profit	SD profit
Panel A: Fixed cost for operator					
C=1, M=0	58.83	5.60	12.99	189,011	284,846
C=2, M=0	**51.25**	**9.50**	**11.04**	**294,700**	**494,065**
C=3, M=0	29.51	30.39	6.17	238,519	602,822
Panel B: Lower base electricity price					
C=1, M=0	82.15	0.33	17.26	263,953	284,886
C=2, M=0	**64.10**	**6.22**	**12.78**	**368,639**	**494,156**
C=3, M=0	38.52	14.55	7.00	311,370	603,181
Panel C: Lower marginal cost of ammonia plant					
C=1, M=1	58.85	2.14	11.25	240,563	284,880
C=2, M=1	**53.00**	**6.78**	**10.36**	**351,135**	**493,410**
C=3, M=1	32.47	18.15	5.86	290,932	600,545
Panel D: Lower conversion rate					
C=1, M=0	42.68	5.27	8.32	137,126	191,089
C=2, M=0	**27.31**	**18.77**	**5.87**	**157,035**	**328,990**
C=3, M=0	10.50	51.24	3.17	84,847	398,163
Panel E: Higher electricity prices					
C=1, M=0	94.91	0.02	21.54	304,938	313,079
C=2, M=0	**76.25**	**5.71**	**15.89**	**438,519**	**543,966**
C=3, M=0	47.98	9.44	9.08	387,918	665,178

Extended analysis – medium gin

Models	Avg. ROIC	Prob. loss	Prob. ROIC > 100	Avg. profit	SD profit
C=0, M=0 EV, *	0.00	0.00	0.00	322,549	109,878
C=1, M=0 EV	132.13	0.00	57.66	424,517	297,249
C=2, M=0 EV	112.01	0.00	31.23	644,104	577,942
C=3, M=0 EV	104.69	0.01	25.79	846,254	854,539
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C=5, M=0 EV	98.96	3.54	23.35	1,227,070	1,391,770
C=6, M=0 EV	**85.76**	**5.10**	**19.02**	**1,237,195**	**1,482,193**
C=7, M=0	73.02	6.08	14.92	1,197,302	1,592,251
C=1, M=1	98.46	0.00	28.51	402,514	296,984
C=2, M=1	95.59	0.00	22.01	633,336	577,545
C=3, M=1	93.74	0.03	21.02	839,793	854,580
C=4, M=1	94.73	1.60	21.71	1,055,860	1,139,546
C=5, M=1	91.96	4.20	20.85	1,220,799	1,392,416
C=6, M=1	80.17	5.46	16.98	1,226,806	1,479,441
C=7, M=1	68.61	6.26	13.53	1,185,122	1,592,734
C=1, M=2	73.52	0.01	14.00	364,869	296,984
C=2, M=2	79.99	0.00	16.39	599,940	577,435
C=3, M=2	82.86	0.18	17.36	814,788	854,714
C=4, M=2	86.17	2.58	18.70	1,035,895	1,139,982
C=5, M=2	85.08	4.61	18.36	1,203,895	1,393,265
C=6, M=2	74.79	5.75	15.37	1,209,904	1,479,485
C=7, M=2	64.36	6.31	12.47	1,167,982	1,593,145

Extended analysis – medium gin

Models	Disc. Avg. profit 12 yrs.	SD disc. profit 12 yrs.	Disc. Avg. ROIC 12 yrs.	Prob. ROIC < 0	Prob. ROIC between 0 & 250	Prob. ROIC between 250 & 500	Prob. ROIC > 500
C=0, M=0 [EV, *]	1,454,760	134,800	0.00	0.00	0.00	0.00	0.00
C=1, M=0 [EV]	1,914,656	377,991	595.93	0.00	0.00	24.13	75.87
C=2, M=0 [EV]	2,905,040	741,192	505.17	0.00	0.00	55.58	44.42
C=3, M=0 [EV]	3,816,778	1,098,925	472.15	0.00	0.00	63.99	36.01
C=4, M=0 [EV]	4,786,208	1,473,196	465.97	0.00	0.60	64.71	34.69
C=5, M=0 [EV]	5,534,335	1,813,371	446.31	0.00	2.28	66.99	30.73
C=6, M=0 [EV]	**5,580,001**	**1,898,134**	**386.78**	**0.00**	**10.56**	**70.83**	**18.61**
C=7, M=0	5,400,078	2,041,002	329.32	0.00	29.05	60.62	10.32
C=1, M=1	1,815,420	377,379	444.10	0.00	0.00	75.51	24.49
C=2, M=1	2,856,472	740,221	431.12	0.00	0.00	76.59	23.41
C=3, M=1	3,787,636	1,098,489	422.79	0.00	1.08	75.27	23.65
C=4, M=1	4,762,144	1,474,845	427.23	0.00	2.40	72.03	25.57
C=5, M=1	5,506,050	1,814,758	414.77	0.00	5.64	70.95	23.41
C=6, M=1	5,533,146	1,891,622	361.60	0.00	16.57	69.63	13.81
C=7, M=1	5,345,144	2,040,417	309.45	0.00	37.58	54.62	7.80
C=1, M=2	1,645,634	377,365	331.59	0.00	11.16	85.83	3.00
C=2, M=2	2,705,850	740,052	360.75	0.00	9.00	80.91	10.08
C=3, M=2	3,674,859	1,098,332	373.70	0.00	9.36	77.07	13.57
C=4, M=2	4,672,099	1,474,955	388.64	0.00	8.52	73.47	18.01
C=5, M=2	5,429,811	1,814,679	383.73	0.00	11.04	71.31	17.65
C=6, M=2	5,456,916	1,891,956	337.33	0.00	25.09	64.35	10.56
C=7, M=2	5,267,835	2,040,863	290.27	0.00	45.86	48.38	5.76