Where Will Food Come From?

A Look at the Potential of Vertical Farming in Norway

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Word Count: 4488

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1. Problem Identification

The world's population is estimated to surpass 10 billion people with 68 percent of the global population expected to live in urban areas by 2050 (United Nations, 2018; United Nations, 2022). These population changes indicates that there is a need for new sources for food production. One such technology is vertical farming.

Vertical farming is where food is grown vertically and nutrients are supplied through hydroponics, aeroponics or aquaponics (Cho, 2011; Zipkin, 2022). A basic requirement for vertical farms is that they are located near population centers with access to major transportation hubs (Zipkin, 2022). This makes them well-suited to provide fresh produce directly to growing urban populations. These types of farms are also resistant to changes in weather and environmental factors such as pests and disease that traditional farming is susceptible to.

This paper will focus on the growth in vertical farming in Norway. Norway is a country that has both the capital and willingness to invest more in vertical farming (Gustavsen et al., 2021). Norway is also a country that has both a growing demand for plant produce, which for this model includes both fruits and vegetables, and is experiencing a decrease in self-sufficiency from its own production (Ministry of Agriculture and Food, 2015; Opplysningskontoret, 2022; Statista, 2022). This is occurring as Norway's urban populations are on the rise (World Bank, 2018). As such, the dynamic problem arises:

> *As Norway's urban population grows,* ***can*** *vertical farming meet the growing demand for plant produce while reducing the need for imports?*

This is an important problem for the Norwegian government as the increase of locally grown produce improves the nation's food resilience and meets its population food demands.

They key reference modes that will be used include total vertical farms, plant produce imported to Norway, and plant produce from Norway all within the years 2013 to 2032. As seen in Figure 1.1, it is desired and expected that vertical farms in Norway increase increasingly to meet the goal of increasing domestic production of plant produce. While there is no sufficient data indicating the number of vertical farms in Norway, the growth rate of the global vertical farm market is expected to be 24.7 percent per year between 2023 and 2028 (Research and Markets, 2023). The European market is also seeing rapid demand for vertical farms which is expected to be reflected in the Norwegian market (Butturini & Marcelis, 2021).

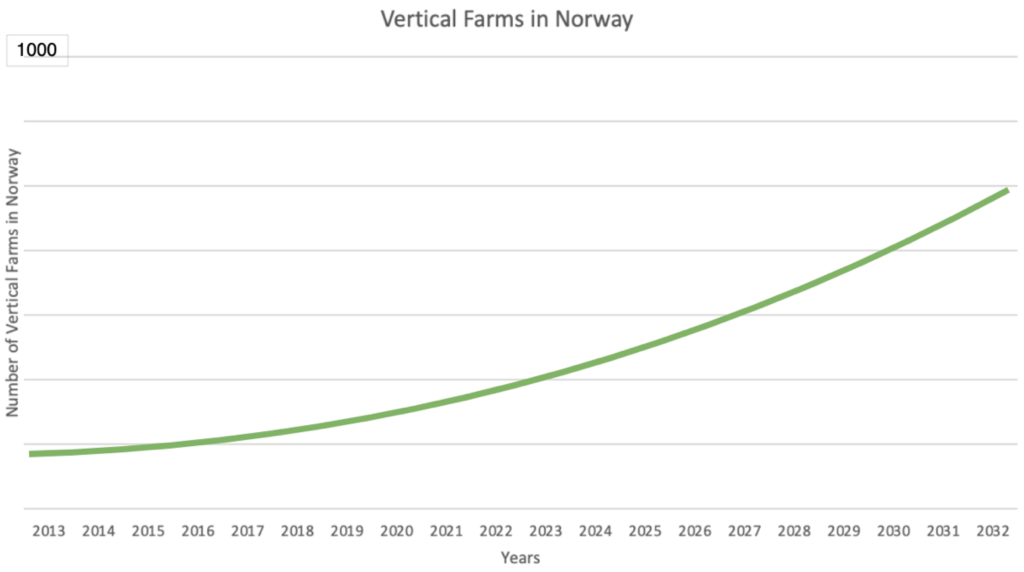

Figure 1.1: Reference Mode for Vertical Farms in Norway

Figure 1.2 shows that historically plant produce imports has been increasing increasingly and that domestic plant produce production has declined in a decreasingly decreasing manner since 1961 (FAO, 2023). The historic data in these figures has been provided by the Food and Agriculture Organization of the United Nations (FAO), but the trends are perceptions I made based on the data. The FAO made changes in their methodology to measure data in 2010, but the overall trends remain consistent. These trends are expected to continue as Norway has been less self-sufficient.

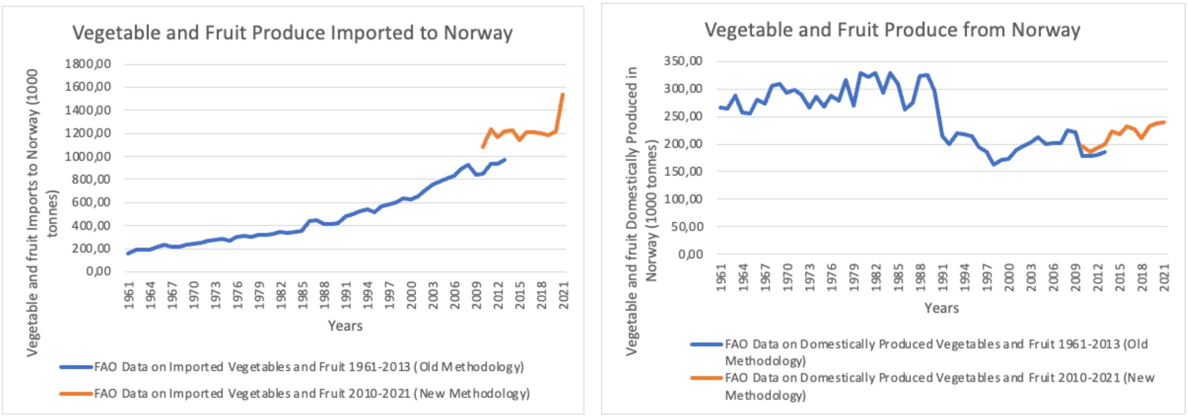

Figure 1.2: Vegetable and Fruit Production Imported vs Vegetable and Fruit Produce from Norway

In Figures 1.3, the red lines indicate the anticipated outlook of plant produce imports and domestic production respectively with the green lines are desired changes. It is desired that the total tons of imported plant produce will decrease increasingly, and the desired tons of plant produce will increase increasingly. This will showcase the desired effect of vertical farming as an effective means of reducing imported produce.

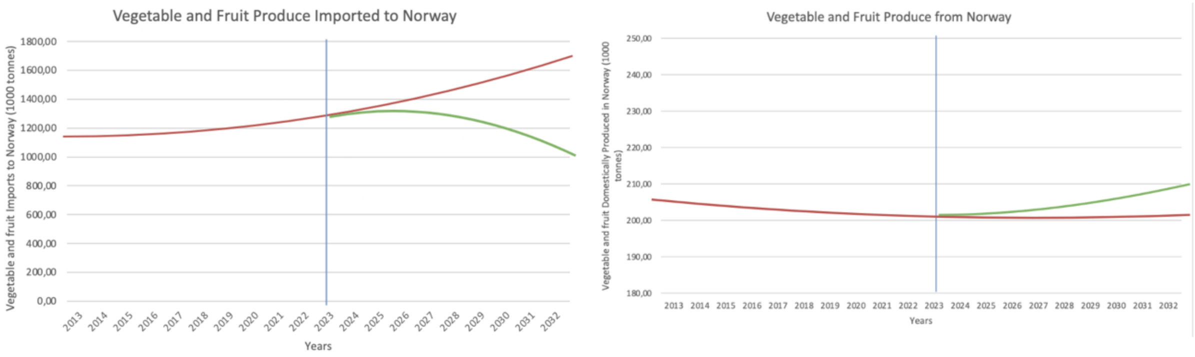

Figure 1.2: Model Reference Mode for Imports and Domestic Production

2. Dynamic Hypothesis

The following Causal Loop Diagram is a simplified version of my model highlighting the **important** feedback loops that can be used to explain my model. It was built using information from academic literature with two sources proving especially beneficial. Song et al. (2021) use a System Dynamics approach when looking at vertical farming implementation in Singapore. Meanwhile, Rajah and Grimeland (2022) help to provide insight on the structure of agricultural models, particularly when it comes to measuring food demand.

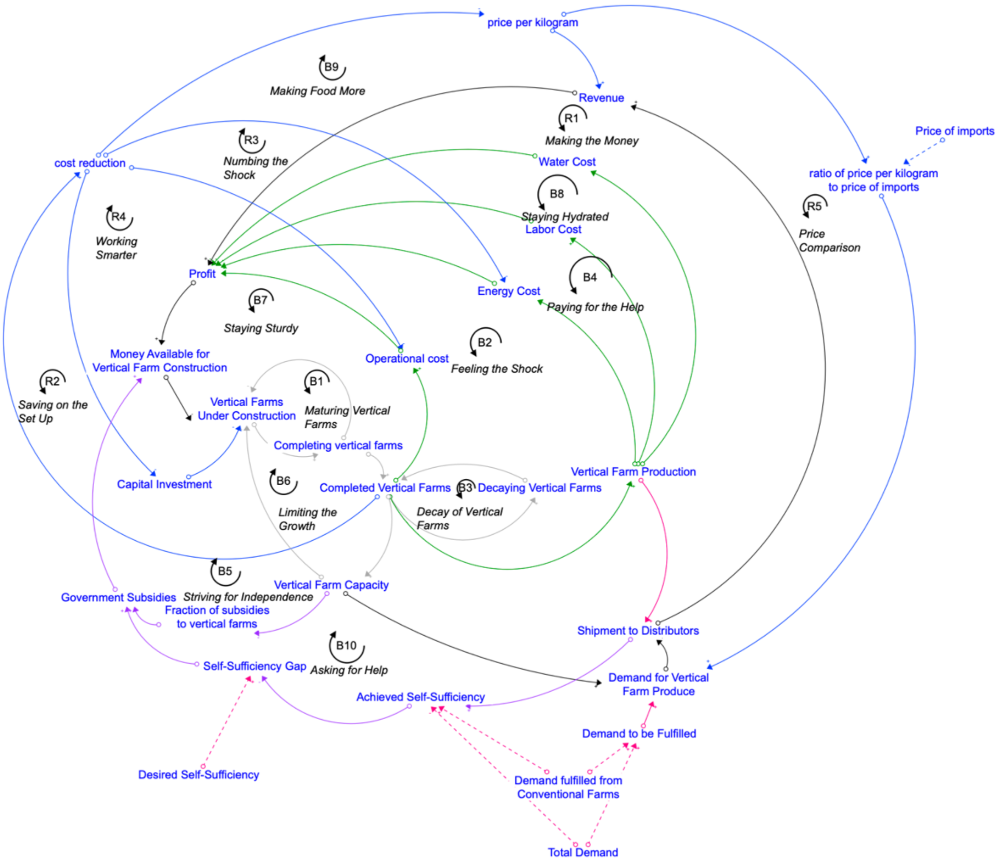

Figure 2.3: Causal Loop Diagram for Vertical Farming in Norway

The Cost Loops

The first series of loops will be described together as they indicate similar impacts on the model. These are balancing loops which include the following: *Feeling the Shock (B2), Paying for the Help (B4), Staying Sturdy (B7), and Staying Hydrated*. *B7* showcases the operational cost loop so that as there are more vertical farms, the total costs of maintaining operating vertical farms increases, lowering the amount of funds available for construction. In *B8,* as the number of vertical farms increase, more water is required per kg of produce which lowers the funds available for construction. The same could be said with *B2* and *B4*. However, these loops indicate the costs of electricity and labor respectively.

These loops are the main costs of vertical farming as identified throughout the literature and business insights (Avgoustaki & Xydis, 2020a; Avgoustaki & Xydis, 2020b; Banerjee & Adenaeuer, 2014; iFarm, 2023; Kobayashi et al., 2022; Song et al., 2021; Pereira, 2023; Zipkin, 2022). A few sources have proven especially helpful in model construction. Avgoustaki & Xydis (2020a) provide the typical cost structure of a vertical farm in Denmark based on plant produce output. This provides helpful insight for the structure of the model considering that Denmark is a neighboring country that is experiencing a growing demand for plant produce and desire to limit vegetable and fruit imports. Kobayashi et al. (2022) have produced a similar study to portray the energy costs of vertical farming in Sweden.

Unlike other types of farming, it is believed that vertical farming will not be impacted by needs related to soil nutrients or expenses related to pests and pathogens (Avgoustaki & Xydis, 2020b; Roberts et al., 2020). Roberts et al. (2020) identify that vertical farms can still be impacted by pests and pathogens but acknowledge that there is not enough scientific investigation into this matter and that vertical farming already minimizes the impacts of these threats. As such, the model does not incorporate these costs.

Income Loop

Vertical farming generates revenue seen in the reinforcing loop *Making Money (R1). R1* showcases the revenue from sales of produce in Norway as determined by the amount of produce shipped to distributors and how close to capacity vertical farms are. Capacity in this instance is an indicator of how much of unfulfilled demand can be met by vertical farming. With a higher capacity, distributors will look to meet more of the demand from vertical farms. This, in combination with the costs, feeds into profit which can then be used to reinvest into constructing more vertical farms. The amount a vertical farm will generate will vary depending on the actual product, but an average price is introduced in my model based on the average costs (Coyle & Ellison, 2017).

Government Subsidy Loops

The next category of feedback loops in the model can be identified as the government subsidy loops. This includes the balancing loop *Striving for Independence (B5)* and *Asking for Help (B10)*. These loops showcase how the increase in vertical farms impact on Norway’s plant produce self-sufficiency. In other words, Norway’s ability to meet the plant produce demands of its citizens. *B10* shows that as the number of new vertical farms increases, the vertical farm capacity increases driving shipments to distributors, and Norway’s self-sufficiency increases as a result. As self-sufficiency increases, the need for government subsidies decreases, reducing the construction of new vertical farms. Meanwhile, *B5* shows a similar story but from the perspective of vertical farm capacity directly. As vertical farm capacity is increased, there is decrease in the fraction of total agricultural subsidies put towards vertical farming as there is a shrinking need for government subsidies as the industry becomes established.

Plant produce self-sufficiency is a growing concern for Norway which has seen a decline in its self-sufficiency (Ministry of Agriculture and Food, 2015). Vertical farms have been a response for many countries looking to new technologies to supplement food demand (Benke & Tomkins, 2017; Song et al., 2021). In the context of Norway, it is unique in that there is already research looking into the willingness of its citizens to pay for new commercial vertical farms (Gustavsen et al., 2022). This indicates that there is public support for the government to help subsidize vertical farming to meet the food demands for fruits and vegetables in Norway.

Economies of Scale Loops

These loops have been identified through the theory of economies of scale. Silberston (1972) provides academic support for this theory in that as an industry increases in scale, it can reduce costs through specialization and the ability to better control input costs of production. This model reflects that in loops *Saving on the Set Up (R2), Numbing the Shock (R3),* and *Working Smarter (R4).* As the vertical farm industry increases in scale, they can bring costs down to operations, upfront capital costs, and energy costs. By lowering costs, price of food can be lowered, increasing revenue as seen in the loop *Making Food More Affordable (B9).* As prices are lowered, produce from vertical farms become more attractive as seen in the loop *Price Comparison (R5).* As price per kilogram becomes closer to the price of imports, or as the ratio of the two decreases, there is an increased demand for vertical farm produce. This drives revenue, more farms, and more cost reduction due to scaling. This increases the amount of profit available to reinvest in vertical farm construction.

Labor costs and water costs were determined to not decrease as these prices are set outside of the actual production process and these vertical farms are already running close to maximum efficacy. Vertical farms recycle close to 100 percent of the water it uses and the technology already makes harvesting very efficient (Avgoustakis & Xydis, 2020b).

Self-Regulation Loops

Balancing loops *Maturing Vertical Farms (B1), Decay of Vertical Farms (B3),* and *Limiting the Growth (B6)* showcase how vertical farm production self regulates. *B1* shows more vertical farms under construction, more farms are being completed which decreases the number of vertical farms under construction. *B3* shows that as there are more completed vertical farms, there are more farms that will decay leaving fewer vertical farms. Both loops also indicate a time delay which limits the speed of these processes. Lastly, *B6* shows as the number of vertical farms reach capacity, there are fewer new farms beginning the construction process, leaving the number of completed vertical farms less than it would be otherwise and the capacity reduced. These loops provide important balancing functions in this model.

3. Validation

Assumptions

Assumptions I made throughout this model were done based on a review of the literature and data sourced from a variety of data banks to provide insight on model structure.

The most prominent assumption is that of my economies of scale loops. I identified that as the vertical farm industry grows, they could bring down costs as is the case with many industries (Silberston, 1972). As such, I am assuming costs would decrease proportionally at the same rate as it would indicate how costs overall would decrease as the vertical farm industry scales. More research is needed. A fraction of this cost savings is shared with the consumer by lowering price.

I made assumptions on the average price per kilogram, but this made sense considering the model structure. This average price was determined to cover the costs plus a twenty percent profit margin. I also made assumptions on my initial stock values and some parameters, but these were supported by evidence from the literature review and hand calibration.

Finally, based on research, I assumed that vertical farms can grow any type of plant produce and that any unmet demand would be fulfilled by imports as Norway is a wealthy country with the means to import food that it cannot produce (Cho, 2011; FAO, 2023).

More information on how this literature impacted specific variables can be found in my documentation in Appendix B.

Model Validation Tests

I performed a series of validation tests to build confidence in my model. I will discuss these tests, but further information can be found in Appendix B.

Structure confirmation test

I performed a structure confirmation test using the literature on vertical farming as well as a variety of data sources to structure the model. The structure was considered a realistic representation of the investment of vertical farming in Norway and the corresponding demand for food.

Parameter confirmation test

The parameters used were backed by the literature review and a variety of professional data sources. They all hold a real world meaning.

Extreme condition test

Extreme condition tests were performed, and the model revealed no unexpected behavior.

Integration test

The model was tested for integration errors by running initially with Euler and then with RK4 at differing DTs. Due to a lack of difference, the Euler simulation method was chosen with DT of 1/8.

Dimensional consistency test

This model holds dimensional consistency with the equations. This is confirmed by the Stella software used for this model.

Behavior sensitivity test

The parameters were tested for behavior inconsistencies. More in depth review of the model behavior can be identified in the model analysis and Appendix C.

Behavior Pattern Reproduction

The reference modes of domestic plant produce, and vertical farms have been met, but the demand from imports is matching the feared reference mode. This is a result of demand increasingly increasing and the demand from vertical farm production not rising fast enough to make a significant impact on unfulfilled demand. As such, demand is met by imports. While not all reference modes were met, this model is still considered valid and useful based on the previous tests.

4. Model Analysis

Base Run Simulation

The graphs shown in Figure 4.1 show the following key performance indicators (KPIs) that I will use to analyze this model. These indicators include demand met from domestic production, demand for imports, completed vertical farms and profit. Using the Stella software, I will use the Loops That Matter tool to help analyze the behavior.

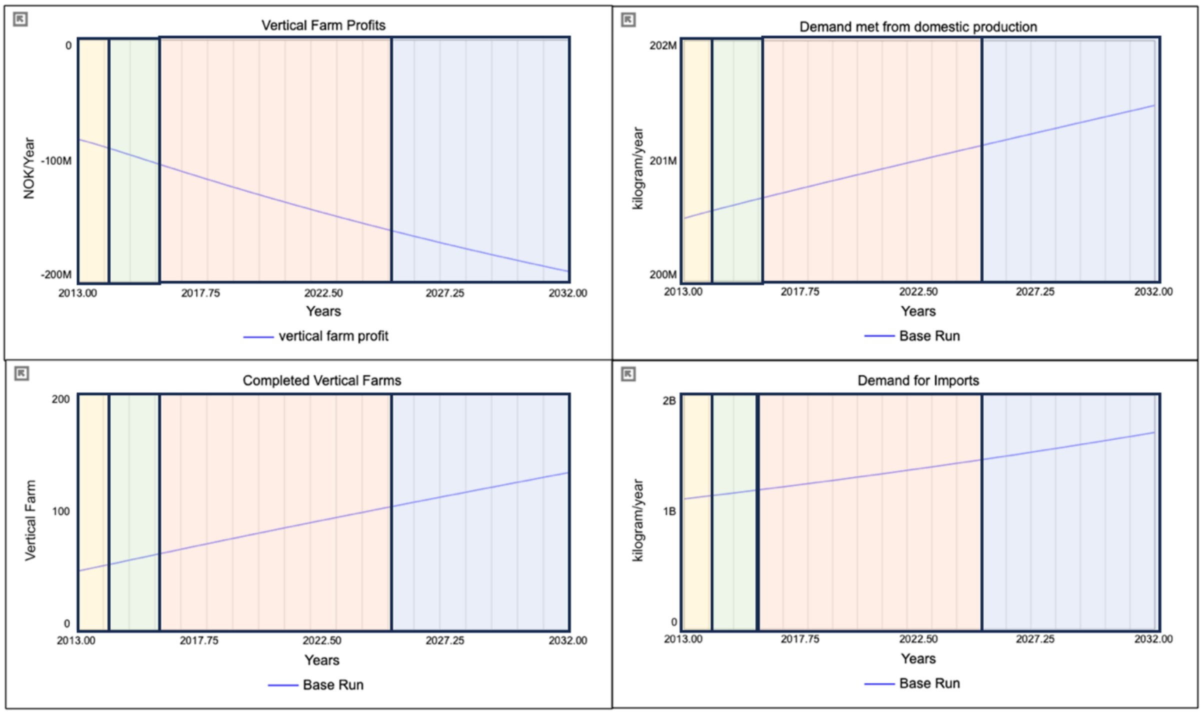

Figure 4.4: Base Run Simulation

As seen in the KPIs, the overall behavior of this model presents increasingly increasing behavior for demand for imports, completed vertical farms and demand met from domestic production, and decreasingly decreasing behavior as seen in profits. For more insight on these variables, profits indicate revenue minus the costs. Demand met from domestic production is a measure of the total shipment to distributors, which represents the amount of vertical farm produce meeting food demand, plus the constant demand fulfilled by conventional farms. Demand for imports is a measure of the remaining demand to be fulfilled minus the demand for vertical farm produce. As noted in my assumptions, it is assumed that any unmet demand will be met by imports. Lastly, completed vertical farms measures the number of vertical farms in operation.

From year 2013 to 2014, as seen in the yellow highlight, loop *Maturing Vertical Farms (B1)* is dominant. In the initial year, the number of vertical farms under construction is low. Over the course of this year, the number of vertical farms under construction are pushed to increase by government subsidies loops. Both *Striving for Independence (B5)* and *Asking for Help (B10)* indicate that since the total number of vertical farms are low, capacity is far from full, and since there is a low self-sufficiency, close to a full amount of the allocated subsidies to vertical farms will be given. This then drives construction of vertical farms. *B1* is dominant in this first year as it prevents an immediate implementation of vertical farms. There is a time delay to construct the farms. Yet, the number of completed vertical farms begin to increase as some of the initial number of vertical farms under construction are completed.

There is still exponential behavior in the other KPIs as the existing number of completed vertical farms are already producing. They increase the amount of domestic produce. It would be fair to guess that as fruit and vegetables are produced and sold profits would increase. This does not occur as the initial costs are more than the revenue. The cost loops remain stronger than the revenue loop *Making the Money (R1)*, lowering profit. However, vertical farms continue to increase as the amount of government subsidies is enough to both cover the negative profits *and* provide enough funding for more construction. Total demand for imports continues to increase similarly as the demand continues to increase faster than vertical farm production can decrease the total demand for imports.

From 2014 to 2016, loop *Decay of Vertical Farms (B3)* comes into dominance which can be seen in the green highlight on the graphs. *B3* grows in strength in the first year as the number of completed vertical farms increase. It then takes over, limiting an immediate decay of vertical farms. Due to a time delay, completed vertical farms are expected to last 30 years. Some will begin the decay process, but they will be prevented from decaying immediately. This leads to the number of vertical farms increasing further during this period.

As the number of verticals farm increases, the vertical farm capacity increases as well. This drives demand met from domestic production as seen in *R1* in which increased vertical farms increases capacity which increases shipments to distributors, increasing revenue, profits and further driving completed vertical farms. However, profits continue to decrease as the cost loops remain stronger than the revenue loop. This does not impact completed vertical farms as government subsidies can still cover the loss in profits *and* provide funds for construction.

Additionally, the price per kilogram is still higher proportionally to price of imports. The economies of scale loops are coming into action, but they are not able to reduce costs or the price per kilogram enough to further drive demand for vertical farm produce. Since the ratio of price per kilogram to price of imports remains above one, loop *Price Comparison (R5)* indicates a limit in how much demand will increase. People are still less willing to purchase vertical farm produce if the price remains higher than imported goods. Revenue increases but not enough to outweigh the cost loops. Profits continue to decline as result. Concurrently, capacity remains relatively low despite increasing which drives *B5* and

B10. This ensures that government subsidies continue to be given to vertical farm construction and the number of vertical farms continue to increase.

It should be noted that the number of vertical farms, and as a result the amount they are able to meet demand, is not increasing quick enough to make an impact on demand for imports. The total demand is continuously increasing due to growing population and consumption per capita, which means the demand for imports continues to increase.

From 2016 to 2025, *B1* is dominant again which can be seen in the red. Government subsidies continue to drive new vertical farms under construction. This coincides with *Saving on the Set Up (R2)* where with more vertical farms, the economies of scale will lower the needed upfront capital investment, further driving new vertical farms under construction. As such, *B1* plays a large role in preventing these farms from being completed immediately. Still, more vertical farms are completed which further drives costs which remain higher than the revenue. The economies of scale do not reduce the price per kilogram so that it becomes lower than price of imports. Costs are not lowered enough to be less than revenue, but there is decreasingly decreasing behavior which indicates that the difference between revenue and expenses is shrinking.

Meanwhile, vertical farm capacity increases, leading to increasingly increasing behavior for the demand met from domestic production. Carrying capacity is still low which allows government subsidies to continue to grow the vertical farm industry despite negative profits. This ensures loop *B1* remains dominant.

Again, it should be noted that demand for imports is continuing to increase increasingly. The total demand is ever rising, and the amount of demand met by vertical farms is not increasing by enough.

2025 to 2032, *B1* and *Feeling the Shock (B2)* are dominant, but *R1* and *R2* are growing in strength. The corresponding behavior can be seen in the blue. *B2* represents how energy costs become more influential in this model. As the number of vertical farms continue to increase, they produce more fruits and vegetables so further costs are incurred. Profits continue to decrease.

However, loops *R1* and *R2* increase in strength. *R1* shows how the revenue loop becomes stronger as the increased number of vertical farms increases capacity and, thus, drives demand for vertical farm produce. Meanwhile, *R2* shows how the economies of scale are becoming increasingly impactful as well. *R2* specifically shows that the upfront costs from capital investment are decreasing enough to further increase the number of vertical farms under construction. This loop also shows how the economies of scale are influencing the model. The reduction in price per kilogram in relation to price of imports helps to further drive revenue and ensure profits decrease decreasingly. This decrease in ratio of price per kilogram to price of imports helps to drive demand for vertical farm produce which further increase increasingly demand met from domestic production. Yet, total demand is still increasing. Vertical farms are not meeting enough of the unfulfilled demand. Thus, demand for imports continues to grow exponentially.

Sensitivity Analysis

Figure 4.2 shows a conclusive table of the sensitivity analysis. For more detailed description, please refer Appendix C.

Model Sector	Parameter	Range	Sensitivity
Vertical Farming Finances	Sensitivity of ratio of vertical farm capacity on cost reduction change rate	0.15-0.45	Not Sensitive
	Indicated cost reduction change rate	(-0.0045)-(-0.0015)	Numerical
	Profit Margin	1-1.8	Numerical
	Fraction of cost reduction to consumers	0.15-0.45	Not Sensitive
	Max cost reduction	0.35-1	Not Sensitive
	Average price of imports	12-90	Behavioral
	Sensitivity of effect of ratio of price per kilogram to price of imports on fraction of demand for vertical farm produce	(-1.5)-(-.5)	Numerical
	Average energy need	136-408	Numerical
	Labor need per kilogram of produce per year	0.00009-0.000027	Not Sensitive
	Water need per kg of produce per year	8.5-25.5	Not Sensitive
	Average operational cost per farm per year	54500-163500	Not Sensitive
	Average cost per L per year	0.005-0.015	Not Sensitive
	Average annual salary Norway	190000-570000	Not Sensitive
	Average cost per kw per year	0.15-0.45	Numerical
	Average capital investment	862500000-287500000	Numerical
	Average cost of commercial space	13664-40992	Not Sensitive
	Indicated size of vertical farm	100-300	Not Sensitive
	Fraction of proift reinvested	0.4-1	Not Sensitive
	Average completion adjustment time	0.5-5	Behavioral
	Initial vertical farms under construction	0-12	Numerical
	Initial completed vertical farms	25-75	Numerical
	Initial vertical farm inventory	96000-288000	Not Sensitive
	Decay adjustment time	15-45	Numerical
Government Subsidies Sector	Desired self-sufficiency	0.5-1	Numerical
	Inflection Point	0.25-0.75	Numerical
	Steepness	2.5-7.5	Numerical
	Government subsidies to agriculture change rate	0.0035-0.0105	Not Sensitive
	Indicated fraction of subsidies to vertical farms per year	0.15-0.45	Numerical
Food Supply	Average output per vertical farm	15500-46500	Numerical
	Food waste rate	0.0025-0.0075	Not Sensitive
	Demand fulfilled from conventional farms Norway	100000000-300000000	Numerical
	Supply coverage	1.0-2.0	Numerical
Food Demand	Birth fraction	0.006-0.018	Not Sensitive
	Death fraction	0.004-0.012	Not Sensitive
	Reference net migration fraction	0.004-0.012	Not Sensitive
	Per capita consumption change rate	0.0035-0.0105	Not Sensitive
	Reference per capita consumption	130-390	Numerical

Figure 4.2: Sensitivity Analysis Overview

Policy Analysis

For this model, I will be testing two policies against the base run and two additional scenarios that I deem possible, if not likely, to occur. Both scenarios will present challenges to establishing vertical farming in Norway. The policy analysis for these additional scenarios can be found in Appendix D. By running these policies in the base run and the additional scenarios, I hope to provide insight into how vertical farms can be implemented more effectively in Norway. The base run shows that while vertical farms are increasing and the demand met from domestic production is increasing, profits are negative and the demand for imports is ever increasing. This indicates that vertical farm industry relies too much on government subsidies to build more farms and that demand for imports are not impacted enough for Norway to be more self-sufficient.

Policy 1: Import Tax.

This is a policy that is meant to showcase a price increase on imports so that import prices, a leverage point, become greater than price per kilogram. The average price of imports is increased by 150 percent in year 2023. Seen in Figure 4.3, a comparison with the base run shows that profits jump into the positive and continue to increase. Demand met from domestic production spikes and then increases more quickly. Meanwhile, there is a slight increase in completed vertical farms.

This policy was introduced as it was identified using the Loops that Matters tool that *Making the Money (R1)* is not dominant but grows in dominance during the base simulation. Meanwhile, *Maturing Vertical Farms (B1)* is dominant for almost the entire run. By increasing the price of imports, this leads to a stronger demand for vertical farm produce. This drives shipments to distributors which increases revenues, boosting profits so that it is positive. This further increases vertical farm construction which increases vertical farm capacity and further increases demand for vertical farm produce. This describes *R1* becoming stronger. Meanwhile, *B1* is becomes slightly less dominant as the ever-increasing profits ensures more farms are under construction and eventually completed. *R1* is more influential on the model.

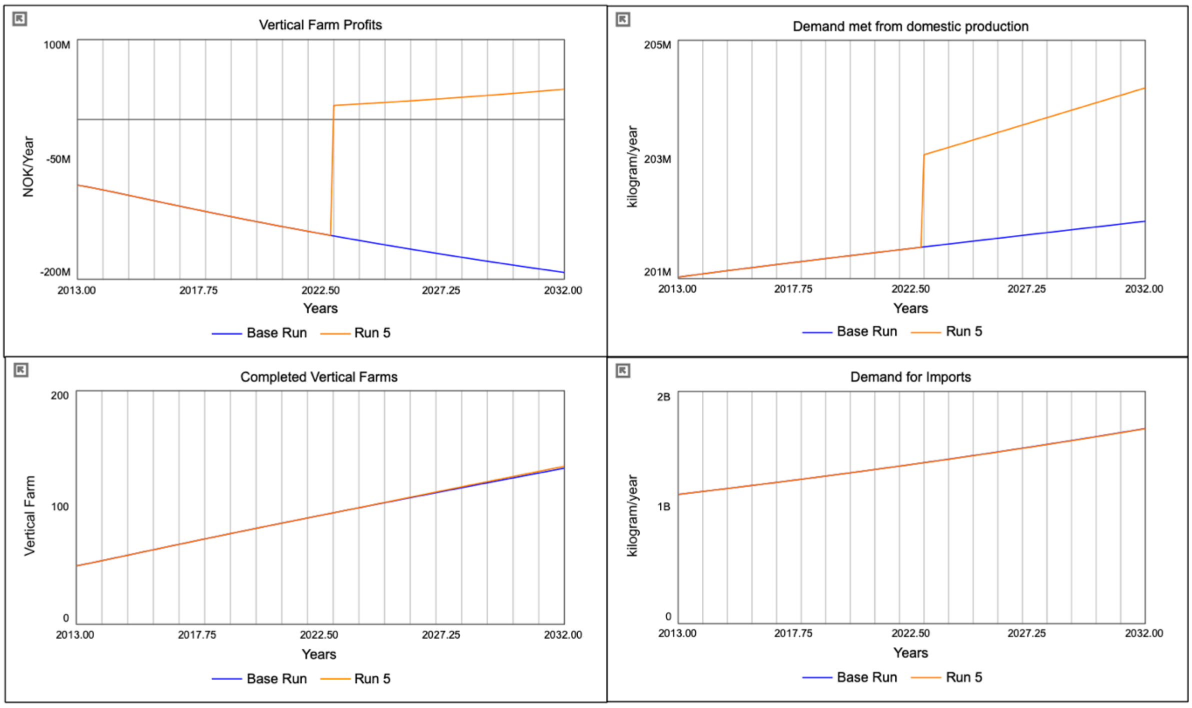

Figure 4.3: Policy 1 on Base Run Simulation

Policy 2: Use of improved energy efficient LEDs.

Policy 2 showcases how the implementation of more efficient LEDs could lower costs. Stella's Loops that Matter identify that *Feeling the Shock (B2)* has a large influence on the model as energy takes up most of the expenses. As such, this loop was targeted with a plausible policy where there is an improvement in energy efficient LEDs (Kobayashi et al., 2022). In 2023, energy efficiency will increase by 25 percent. This improved efficacy will mean energy need for both lighting and the temperature control requirements to counteract the heat generated from the lighting will be reduced.

By lowering energy need, *B2* is weakened. The impacts can be seen in Figure 4.4. Profits increase because of a weaker *B2*. This does not lead to more vertical farms as profits remain negative which indicates that subsidies still drive construction. Meanwhile, demand met from domestic production increases as the lower energy need reduces price per kilogram. Price per kilogram is determined to cover costs plus a profit margin. With a lower price per kilogram relative to imports, this drives more demand for vertical farm production.

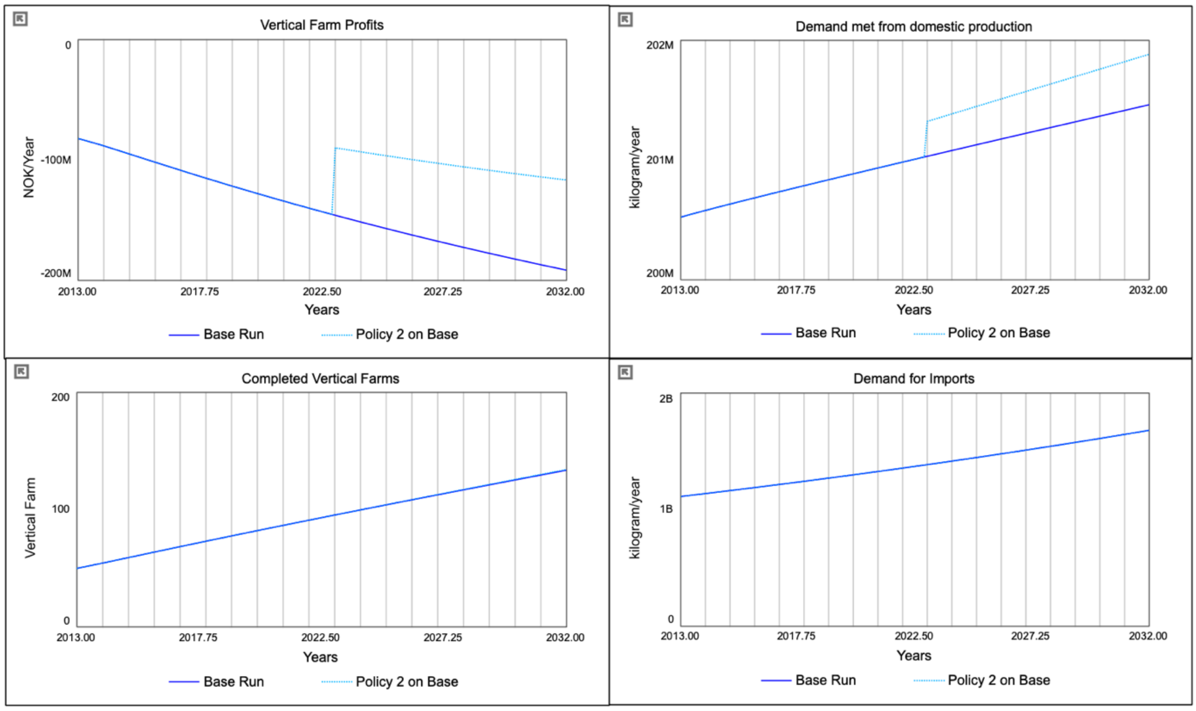

Figure 4.4: Policy 2 on Base Run Simulation

Policy 1 + Policy 2 on Base Run:

Both policies were implemented together on the base run to test the effect. The results can be seen in Figure 4.5. There is a significant increase in profits which is caused by strengthening *R1* in Policy 1 and weakening *B2* in Policy 2. *R1* is also strengthened by the reduction of energy need from Policy 2 which increases demand met from domestic production. However, there is still only a slight change in completed vertical farms which is coming primarily from Policy 1. Demand for imports remains unchanged. These policy implementations are not enough to impact demand for imports.

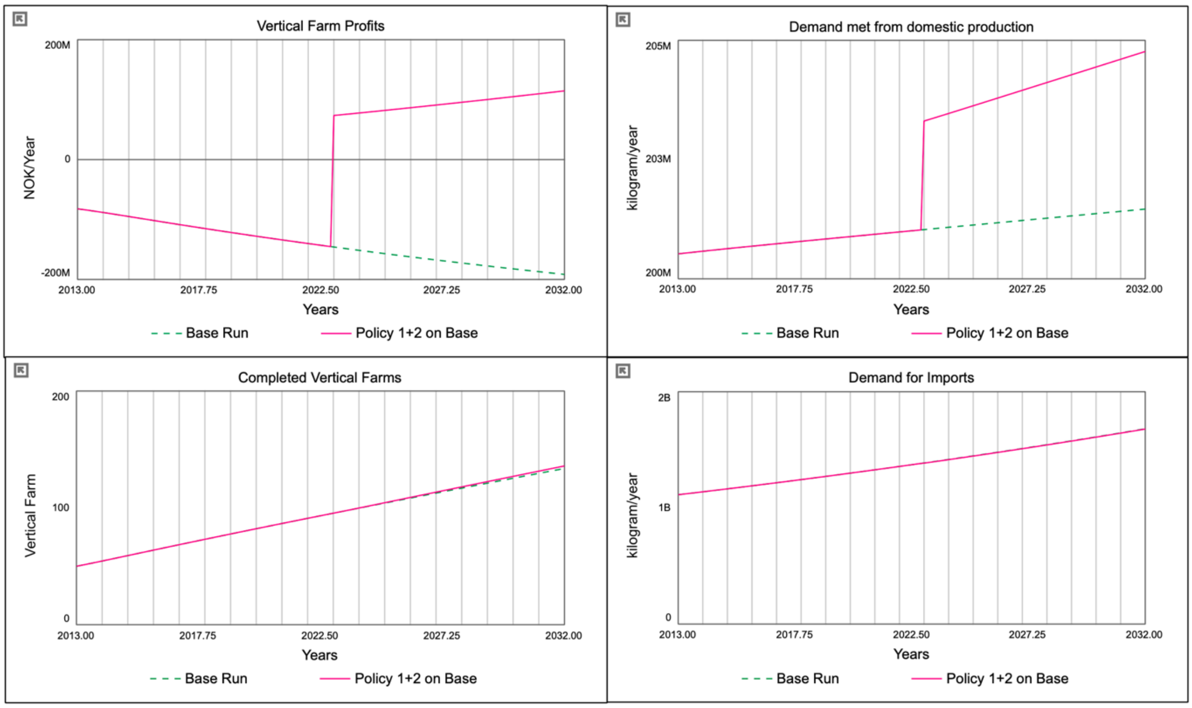

Figure 4.5: Policy 1 and 2 on Base Run Simulation

5. Conclusion

The run of the polices on the base simulation, and both scenarios in Appendix C, indicate limitations of the model. Since population is exogenous and driving total demand, it will take extreme measure to increase domestic production within a limited time frame to begin lowering demand for imports. As such, the model as it is currently constructed indicates that Norway will continuously need to rely on imports to meet their population's plant produce demands. Given the current structure of the model, Policy 1 would prove to be the most effective regardless of the scenario. It would ensure demand shifts towards vertical farm produce and ensure the industry is self-sustaining financially. This is significant as vertical farming will need to rely substantially on government subsidies to survive otherwise. Yet, this policy would prove the most difficult to implement as import taxes are often dictated by treaties and other government policies. The feasibility of this policy will need to be further researched.

There are other limitations that should be noted. Aspects of this model that I would like to further research include the implementation of soft modelling. These aspects would showcase the influence of marketing, word-of-mouth, and general perception of vertical farm produce. Vertical farm produce is often seen as higher quality albeit less natural than conventional or greenhouse production (Coyle & Ellsion, 2017). These impacts that flush out a more complicated decision-making process for consumers can showcase how the vertical farm industry can be more impactful supply Norway with plant produce more quickly and significantly. This can prove essential as the existing model does not show many leverage points and that this model is not able to feasibly impact demand for imports. I notice in my sensitivity analysis it could only do so by impacting consumption and demand fulfilled from conventional farming. Increasing consumption for fruits and vegetables is desired by the Norwegian government and the output from conventional farming is unlikely to increase (Opplysningskontoret, 2022; FAO, 2023). By including these aspects, I can further introduce clarity into how vertical farming in Norway can meet the demand for plant produce while reducing the reliance on imports.

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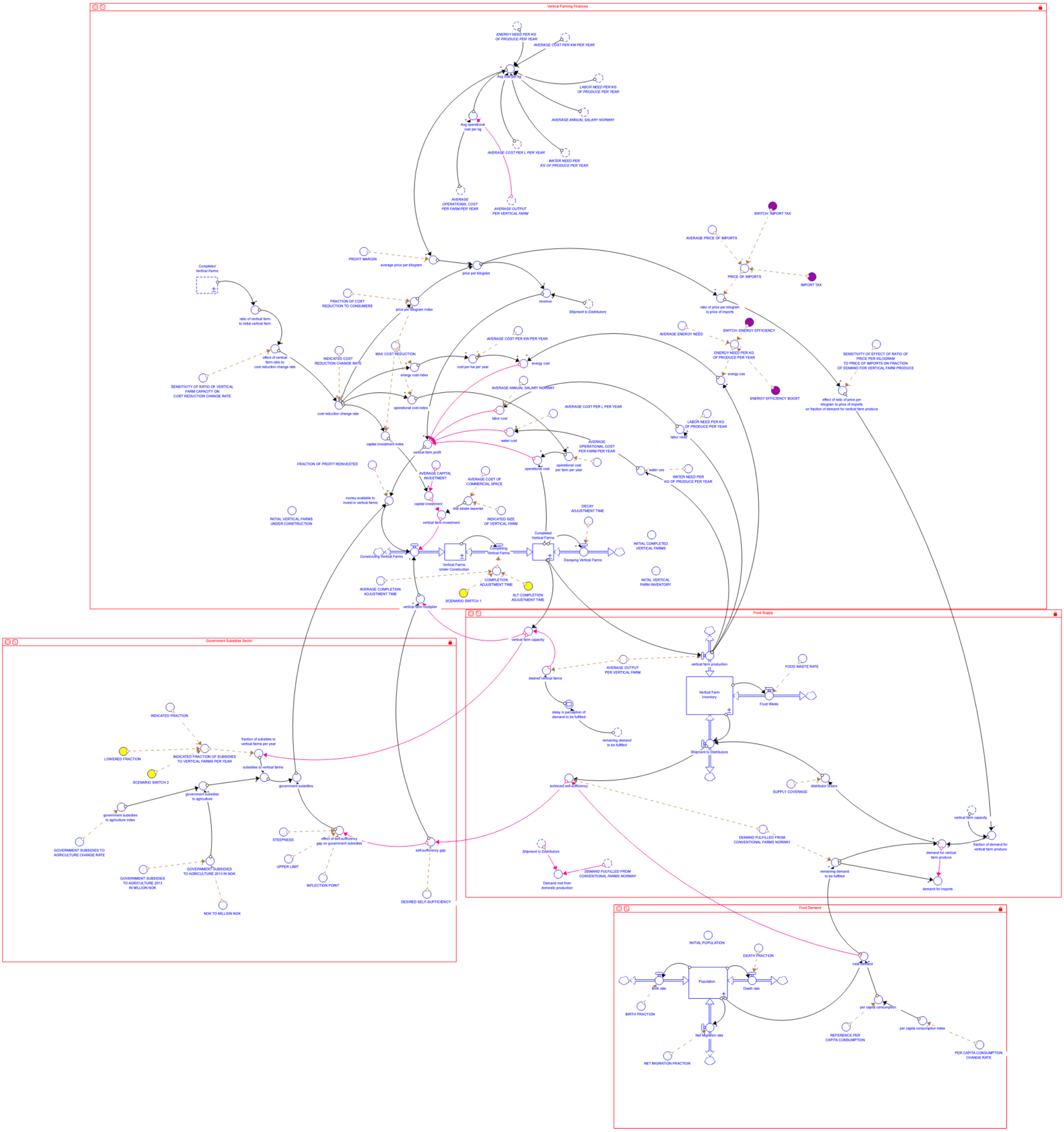
Appendix A: Model Structure



Appendix B: Documentation

Simulation Experiment Report

Modelling Software: Stella 3.5

Start Time: 2013

End Time: 2032

Integration Method: Euler

Time Units: Years

DT: 1/8

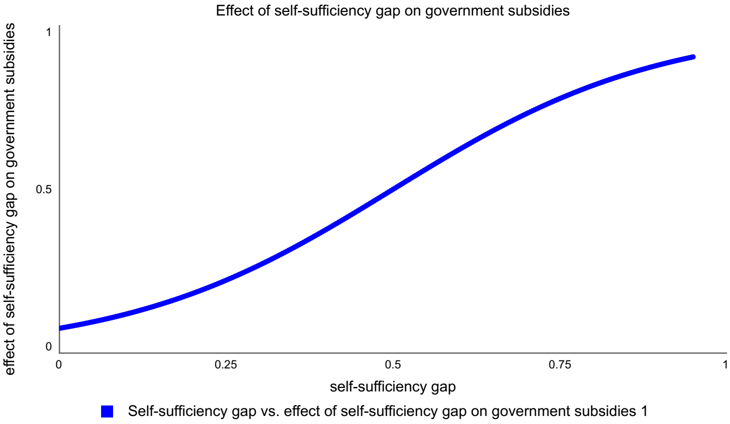
	Equation	Units	Documentation
BIRTH_FRACTION	.012	1/year	Birth Rate data was found in Statistics Norway (2022; 2023a). The data used from this source takes the Live Births in 2013 divided by the Population in 2013.This value is the Birth Fraction found in 2013 which is then used for this model.
Birth_rate	BIRTH_FRACTION*Population	Person/ Years	The birth rate is rate at which new people are born. It is an inflow into population. Births arise from the birth fraction and the population. As population increases, births increase. As population decreases, births decrease.
DEATH_FRACTION	.008	1/year	Death Rate data was found in Statistics Norway (2022; 2023a). The data used from this source takes the Deaths in 2013 divided by the Population in 2013.This value is the Death Fraction found in 2013 which is then used for this model.
Death_rate	DEATH_FRACTION*Population	Person/ Years	The death rate is the rate at which new people die. It is an outflow from population. Deaths arise from the death fraction and the population. As population increases, deaths increase. As population decreases, deaths decrease.
INITIAL_POPULATION	5051275	person	This is the initial population in the year 2013. This data was found from Statistics Norway database (2022).
NET_MIGRATION_FRACTION	0.008	1/year	This is the time in which vertical farms take to be completed from the beginning of construction. Most vertical farms are located in urban settings. As such, they use existing infrastructure. As such, I am assuming that most farms take one year to be completed. This is supported by literature review in which vertical farms are built using existing infrastructure (Avgoustakis & Xydis, 2020a).

Net_Migration_rate	Population*NET_MIGRATION_FRACTION	Person/Years	The net migration rate is rate at which new people are born. It is a an inflow into population. Net migration arises from the net migration fraction and the population. As population increases, net migration increases. As population decreases, net migration decreases.
per_capita_consumption	REFERENCE_PER_CAPITA_CONSUMPTION*per_capita_consumption_index	kilogram/person/year	Per capita consumption is the amount of plant produce consumed. It is assumed that it will increase each year. The per capita consumption is determined by the reference per capita consumption multiplied by the per capita consumption index.
PER_CAPITA_CONSUMPTION_CHANGE_RATE	0.00693	1/year	Per capita consumption change rate is the amount per capita consumption changes each year. This number was found by inserting the per capita supply of fruits and vegetables from FAO (2023) using their new methodology data from 2013-2021. This data was then calibrated with the model to find the appropriate slope.
per_capita_consumption_index	EXP((PER_CAPITA_CONSUMPTION_CHANGE_RATE)*(TIME-STARTTIME))	1	This per capita consumption index showcases the effect the per capita consumption change rate will have on the reference per capita consumption. It will show that with each year from the start time, the per capita consumption will increase exponentially by the per capita consumption change rate multiplied by the number of years that have passed. Exponential increase will occur as Norway has seen a shift in diets pushed by the government in a plan that pushes Norwegians to eat 5 servings of fruits and vegetables per day. Only a fraction of the population does this at the moment (Opplysningskontoret, 2022).
Population(t)	Population(t - dt) + (Birth_rate + Net_Migration_rate - Death_rate) * dt	Person	This is the stock of population. It is increased by the inflow of birth rate and the inflow net migration. Death rate decreases population. The initial value of population is determined by Initial Population.
REFERENCE_PER_CAPITA_CONSUMPTION	260.03	kilogram/person/year	Reference per capita consumption is the amount of food consumed per capita in 2013. This data point was found from the FAO (2023) which measures food consumption per capita.
total_demand	Population*per_capita_consumption	kilogram/year	Total demand is the demand in kilograms Norway desires. This is determined by multiplying per capita consumption and the total population.
"achieved_self-sufficiency"	(Shipment_to_Distributors+DEMAND_FULFILLED_FROM_CONVENTIONAL	1	Achieved self-sufficiency is the proportion of food demand that is met by domestic production in Norway. Domestic production in this instance includes both vertical farm produce as determined by shipment to distributors which measures how much demand vertical farms meet and the

	_FARMS_NORWAY)//total_demand		demand fulfilled from conventional farms Norway which measures how much demand is met by existing conventional farms in Norway.
AVERAGE_OUTPUT_PER_VERTICAL_FARM	31032.54	kilogram/Vertical Farm/year	This value indicates the average output a vertical farm has per year. This value was determined by looking at Song et al. (2021) in which they measured the average output for a vertical farm in Singapore that was approximately 30 meters squared in size and then scaled to meet the size of the assumed average size of a commercial vertical farm in Norway. While the output can change depending on the produce, this provides a good estimate as to how much a farm could produce. It should be noted that even though Singapore is in a different environment, vertical farms are isolated, climate controlled environments meaning that plant produce output will be very similar if not the same.
delay_in_perception_of_demand_to_be_fulfilled	SMTH1(remaining_demand_to_be_fulfilled, 1)	kilogram/year	This is a delay converter which represents a smooth function. This indicates that remaining demand to be fulfilled will have a perception delay of one year before it affects the desired number of vertical farms. In other words, there is an information delay in determining how many vertical farms are desired.
demand_for_imports	remaining_demand_to_be_fulfilled-demand_for_vertical_farm_produce	kilogram/year	Demand for imports indicates how much demand is expected to be fulfilled by imports. There is an assumption that whatever demand is not fulfilled by domestic production will be imported instead. As such, demand for imports is determined by subtracting demand for vertical farm produce from remaining demand to be fulfilled.
demand_for_vertical_farm_produce	remaining_demand_to_be_fulfilled*fraction_of_demand_for_vertical_farm_produce	kilogram/year	The demand for vertical farm produce is the amount of demand that is desired from vertical farm produce. This is determined from the multiplication of remaining demand to be fulfilled and the fraction of demand for vertical farm produce.
DEMAND_FULFILLED_FROM_CONVENTIONAL_FARMS_NORWAY	200000000	kilogram/year	This is an assumed value of the amount of tonnes that conventional farms produce each year. This value is determined by existing data for the amount of plant produce produced in Norway and is kept constant as the amount of produce from Norwegian plant produce farms has been largely constant over the past several years (FAO, 2023).
Demand_met_from_domestic_production	DEMAND_FULFILLED_FROM_CONVENTIONAL_FARMS_NORWAY+Shi	kilogram/year	This variable is a key performance indicator that determines how much plant produce is coming from Norway. It adds vertical farm production by the demand fulfilled from conventional farms.

	pment_to_Distributors		
desired_vertical_farms	delay_in_perception_of_demand_to_be_fulfilled/AVERAGE_OUTPUT_PER_VERTICAL_FARM	Vertical Farm	This is the desired number of farms that Norway should have to meet the population's food demand. This is determined by the demand to be fulfilled and the average output per vertical farm to determine.
distributor_orders	MAX(SUPPLY_COVERAGE*demand_for_vertical_farm_produce, 0)	kilogram/year	This is the number of orders that distributors desire from vertical farms to meet the plant produce demand in Norway. This is determined by supply coverage and demand for vertical farm produce. This equation includes a MAX function as it is assumed that if demand for vertical farm produce falls below zero, there will be no distributor orders for vertical farm produce.
Food_Waste	FOOD_WASTE_RATE*Vertical_Farm_Inventory	kilogram/year	Food waste is an outflow from Vertical Farm Inventory. It indicates the rate at which food is wasted in vertical farms and is ultimately not consumed by Norwegians. This outflow is determined by Vertical Farm Inventory and Food Waste Rate. It indicates that each year a fraction of the Vertical Farm Inventory is lost to food waste.
FOOD_WASTE_RATE	.005	1/year	This is an assumed value of fractional food waste from vertical farming. It is known that vertical farming has a significantly lower waste fraction than conventional farming (Avgoustakis & Xydis, 2020b). They use up to 100 percent less land than conventional farms to produce the same amount of produce (ibid). Meanwhile, it has been previously assumed that traditional farms waste up to 5 percent of their produce (Rajah & Grimeland, 2022). With the idea that vertical farms can be 100 percent more efficient in terms of land use, I assume that their food waste is also reduced by 100 percent.
fraction_of_demand_for_vertical_farm_produce	vertical_farm_capacity*effect_of_ratio_of_price_per_kilogram_to_price_of_imports_on_fraction_of_demand_for_vertical_farm_produce	1	The fraction of demand for vertical farm produce is the fraction of unfulfilled demand that is desired to be filled by vertical farm produce. This variable is determined by multiplying the effect of ratio of price
remaining_demand_to_be_fulfilled	MAX(total_demand-DEMAND_FUL	kilogram/year	The remaining demand to be fulfilled is the demand that has not been met by conventional farms in Norway. This is determined by the total demand which is then subtracted by

	FILLED_FROM_CONVENTIONAL_FARMS_NORWAY, 0)		demand fulfilled from conventional farms in Norway. This variable includes a MAX function as it assumes that if total demand ever falls below zero, then it indicate that there is no demand to be fulfilled.
Shipment_to_Distributors	MIN(Vertical_Farm_Inventory/DT, distributor_orders)	kilogram/year	This is the outflow in which Vertical Farm Inventory is shipped to distributors. Shipments arise from distributor orders unless the amount of inventory is lower than the distributor orders. A MIN function is introduced so that normally shipment of distributor orders determines the outflow of inventory to meet the demand for plant produce. However, when distributor orders exceed inventory, inventory will be released within one DT, or as quickly as possible, in order to meet distributor orders.
SUPPLY_COVERAGE	1.5	1	This is an assumed value which determines the expected amount distributors want to cover in excess of the unsatisfied demand. This parameter was created with insight from Rajah and Grimeland (2022). It is assumed that distributors would want to order 50 percent more than what they need to ensure that they can supply demand.
vertical_farm_capacity	Completed_Vertical_Farms//desired_vertical_farms	1	Vertical farm capacity indicates how close the existing number of functioning farms are to the desired number of vertical farms. This is done proportionally. A value of 1 indicates that the desired number of vertical farms is fulfilled and a value of 0 indicates that none of the desired vertical farms are fulfilled.
Vertical_Farm_Inventory(t)	Vertical_Farm_Inventory(t - dt) + (vertical_farm_production - Food_Waste - Shipment_to_Distributors) * dt	kilogram	The stock of vertical farm inventory increases due to the inflow of vertical farm production and decreases as a result of the outflows of food waste and shipment to distributors. The initial value of vertical farm inventory is given by initial vertical farm inventory.
vertical_farm_production	(AVERAGE_OUTPUT_PER_VERTICAL_FARM*Completed_Vertical_Farms)	kilogram/year	Vertical farm production is the inflow to vertical farm inventory. This arises from the number of completed vertical farms multiplied by the average output per vertical farm. With more completed vertical farms, there will be an increase in production of plant produce per year. This then increases the total of vertical farm inventory.
"DESIRED_SELF-SUFFICIENCY"	1	1	This is an assumed value. It is assumed that Norway would want to be 100 percent self-sufficient to meet the food demands of its population without relying on imports. This is an assumption based on literature review in which Norway sees itself increasing self-sufficiency and that to be self-sufficient, from an emergency preparedness perspective,

			Norway "should produce as much as possible of the food its citizens actually need" (Ministry of Agriculture and Food, 2015). In this context we are also assuming that Norway wants to be completely self-sufficient in terms of its plant produce.
"effect_of_self-sufficiency_gap_on_government_subsidies"	UPPER_LIMIT//(1+EXP(STEEPNESS*(INFLECTION_POINT-"self-sufficiency_gap")))	1	This is the effect of the self-sufficiency gap on government subsidies. It is assumed that the government will not want to spend the full amount of its available subsidies and allocate what is not used to other initiatives. As such, the self-sufficiency gap will indicate how much of the subsidies are used. This is s-shaped with an inflection point of 0.5 of the self-sufficiency gap and an upper limit of 1. This indicates that when self-sufficiency gap is 0.5, the government will use only half of its allocated subsidies for vertical farms. When the gap is above 0.5, it will look to use an increased amount of its subsidies as the government is looking to lower the self-sufficiency gap through increased subsidies. It will do so decreasingly in hopes that the government will not need to use the full allocation and use funds for other agricultural initiatives. At self-sufficiency gap of 1, the full subsidies will be used. At a gap of less than 0.5, the government will increasingly decrease the amount of funds it spends on its vertical farming as there is a smaller need for funding based on self-sufficiency in Norway. At a gap of 0, the government will not put any money towards vertical farms. 
fraction_of_subsides_to_vertical_farms_per_year	INDICATED_FRACTION_OF_SUBSIDIES_TO_VERTICAL_FARMS_PER_YEAR*(1-vertical_farm_capacity)	1/year	This variable is the actual fraction of subsidies to vertical farms per year. This is determined by multiplying vertical farm capacity and indicated fraction of subsidies to vertical farms per year. This indicates that as the capacity gets closer to zero, the Norwegian government will be more incentivized to use the full indicated fraction they are aiming to help construct vertical farms. As capacity grows, the Norwegian government will be less incentive to use the full

			fraction as they see that their vertical farms are closer to desired and will push funding to other initiatives.
government_subsides_to_agriculture	GOVERNMENT_SUBSIDIES_TO_AGRICULTURE_2013_IN_NOK*government_subsidies_to_agriculture_index	NOK	This variable is the amount of government subsidies to agriculture. It is increased each year by multiplying the government subsidies to agriculture 2013 and the government subsidies to agriculture index.
government_subsidies	"effect_of_self-sufficiency_gap_on_government_subsidies"*subsidies_to_vertical_farms	NOK/Year	This variable indicates how much money is put towards vertical farming from the Norwegian government. This is determined by multiplying subsidies to vertical farms and the effect of self-sufficiency gap on government subsidies.
GOVERNMENT_SUBSIDIES_TO_AGRICULTURE_2013_IN_MILLION_NOK	18085	Million NOK	This is the government subsidies given to agriculture in 2013 from the Norwegian government in million NOK (Statistics Norway, 2023c).
GOVERNMENT_SUBSIDIES_TO_AGRICULTURE_2013_IN_NOK	NOK_TO_MILLION_NOK*GOVERNMENT_SUBSIDIES_TO_AGRICULTURE_2013_IN_MILLION_NOK	NOK	This is the amount of government subsidies to agriculture in 2013 from the Norwegian government in NOK. It is determined by NOK to million NOK and government subsidies to agriculture 2013 in million NOK.
GOVERNMENT_SUBSIDIES_TO_AGRICULTURE_CHANGE_RATE	0.00721	1/year	This value indicates the rate of change agricultural subsidies will increase each year. This is determined by calibrating the model to existing data (Statistics Norway, 2023c).
government_subsidies_to_agriculture_index	EXP((GOVERNMENT_SUBSIDIES_TO_AGRICULTURE_CHANGE_RATE)*(TIME-STARTTIME))	1	This government subsidies to agriculture index showcases the effect the government subsidies to agriculture change rate will have on the government subsidies to agriculture 2013. It will show that with each year from the start time, the government subsidies to agriculture will increase exponentially by the government subsidies to agriculture change rate multiplied by the number of years that have passed. This increase in government subsidies can be explained by a push by the Norwegian government to increase their funding to agriculture in order to increase their self-sufficiency and a push by farmers themselves to get more funding (Berglund, 2022; Ministry of Agriculture and Food, 2015).

INDICATED_FRACTION	0.3	1/year	This is the indicated fraction that will be impacted by the policy of Lowered Subsidies Scenario. Please refer to indicated fraction of subsidies to vertical farms per year for more information on the meaning of this value.
INDICATED_FRACTION_OF_SUBSIDIES_TO_VERTICAL_FARMS_PER_YEAR	INDICATED_FRACTION*(1-SCENARIO_SWITCH_2) + (INDICATED_FRACTION-LOWERED_FRACTION)*SCENARIO_SWITCH_2	1/year	This is an assumed value that the Norwegian government wants to put indicated fraction of its food and agriculture funds towards vertical farming. This value is assumed based on Norway's desire to be self-sufficient but with the acknowledgment that it wants to protect its existing industries mostly in fishing and meat production. It already is largely or completely self-sufficient for meat and fish demands (Ministry of Agriculture and Food, 2015). However, these industries are known to be protected and subsidized with much funding going to protect existing farmers (Berglund, 2022). As such, it is assumed that Norway will look to invest, but will not be able politically to invest a majority of its funds towards this goal.
INFLECTION_POINT	.5	1	This is an assumed point at which the s-shaped impact of self-sufficiency gap is inflected. This indicates that when self-sufficiency gap is 0.5, the government will use only half of its allocated subsidies for vertical farms. When the gap is above 0.5, it will look to use a decreasingly increased amount of its subsidies as the government is looking to lower the self-sufficiency gap through increased subsidies. It will do so decreasingly in hopes that the government uses funds for other agricultural initiatives. At a gap of less than 0.5, the government will increasingly decrease the amount of funds it spends on its vertical farming as there is a smaller need for funding based on self-sufficiency in Norway.
LOWERED_FRACTION	STEP(.2, 2023)	1/year	This variable indicates an alternative scenario in which there is an uncontrolled delay in the completion of vertical farms. Due to supply chain issues outside of the control of the vertical farm industry, it will take five years instead of one to complete vertical farms.
NOK_TO_MILLION_NOK	1000000	NOK/Million NOK	This is a parameter to convert one million Norwegian Kroner (NOK). It identifies that there are one million NOK in a unit of million NOK.
SCENARIO_SWITCH_2	0	1	This is a switch variable that turns on and off the Lowered Subsidies Scenario.
"self-sufficiency_gap"	"DESIRED_SELF-SUFFICIENCY" -"achieved_self-sufficiency"	1	This variable considers the gap between the desired self-sufficiency and the achieved self-sufficiency. As this gap grows, it indicates that Norway is decreasingly self-sufficient. As this gap shrinks, it indicates that Norway is increasingly self-sufficient.

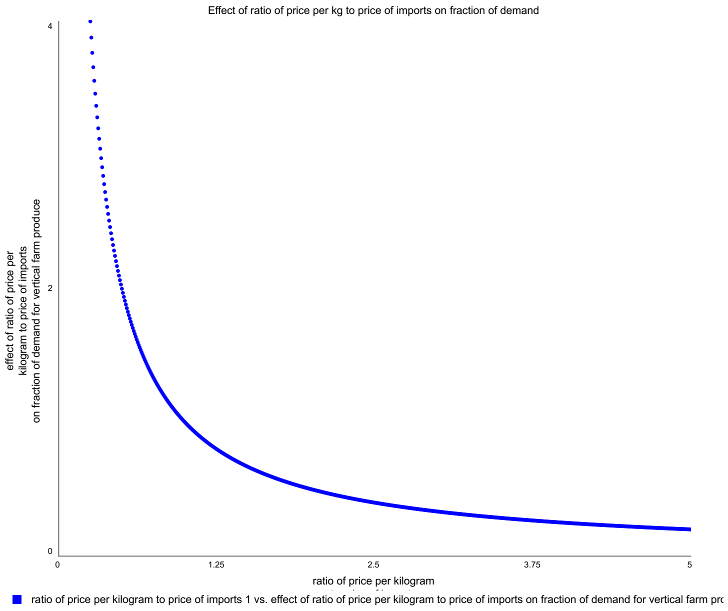
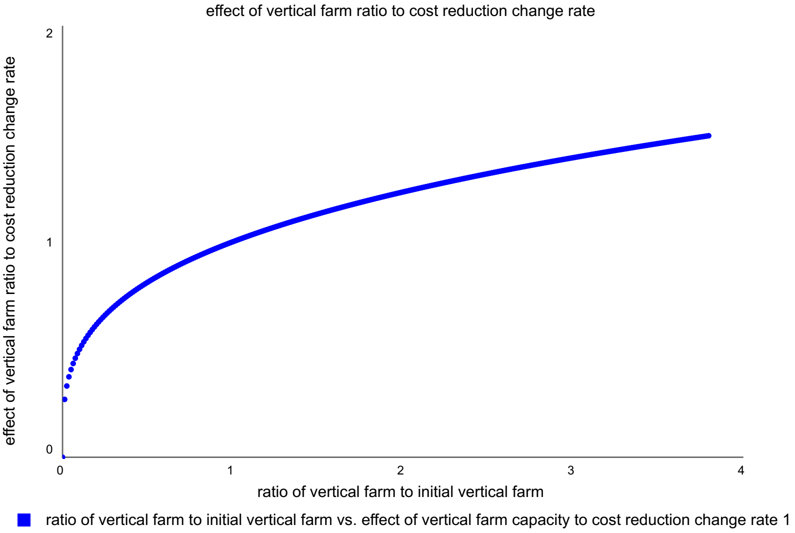
STEEPNESS	5	1	This value indicates the steepness of the slope of the s-shaped effect of self-sufficiency gap on government subsidies.
subsidies_to_vertical_farms	fraction_of_subsides_to_vertical_farms_per_year*government_subsides_to_agriculture	NOK/year	This variable determines the amount of total agriculture subsidies is allocated to vertical farms. It is determined by the fraction of subsidies to vertical farms per year multiplied by the government subsidies to agriculture.
UPPER_LIMIT	1	1	This is the maximum value at which self-sufficiency gap will impact government subsidies. At 1, full government subsidies will be used.
ALT_COMPLETION_ADJUSTMENT_TIME	STEP(4, 2023)	year	This variable indicates an alternative scenario in which there is an uncontrolled delay in the completion of vertical farms. Due to supply chain issues outside of the control of the vertical farm industry, it will take five years instead of one to complete vertical farms.
AVERAGE_ANNUAL_SALARY_NORWAY	378789.36	NOK/Year/Worker	This value is the average annual salary of a skilled agricultural worker in Norway. This value was found by identifying the monthly earnings of an average worker matching this skillset in 2022 (Statistics Norway, 2023d). This number was then multiplied by 12 to get the wage per year. This number was then converted to 2013 NOK value.
AVERAGE_CAPITAL_INVESTMENT	575000000	NOK/Vertical Farm	This variable determines the up front capital investment to establish a vertical farm. This value was determined by literature review. Avgoustakis and Xydis (2020a) found the upfront costs of installation of all of the necessary equipment for a vertical farm. This value was in euros and converted to 2013 NOK. This value provides a good estimation of how much it would take to re-purpose existing commercial space to commercial vertical farm needs.
AVERAGE_COMPLETION_ADJUSTMENT_TIME	1	year	This is the time in which vertical farms take to be completed from the beginning of construction. Most vertical farms are located in urban settings. As such, they use existing infrastructure. As such, I am assuming that most farms take one year to be completed. This is supported by literature review in which vertical farms are built using existing infrastructure (Avgoustakis & Xydis, 2020a).
AVERAGE_COST_OF_COMMERCIAL_SPACE	27328	NOK/m2	This parameter indicates the average cost per meter squared to purchase commercial real estate in Norway. This was done by using Finn.no (2023) and identifying 14 commercial properties currently available in Norway's urban cities that were between 200 and 300 meters squared in size. The areas identified include Bergen, Oslo, Kristiansand, and Stavanger. These sites were chosen as vertical farming is a agricultural

			system used to feed urban centers and would thus be located in urban areas. The size of these spaces were narrowed down due to an assumption that the typical vertical farm for commercial use will be between 200-300 meters squared. This was influenced by an existing Norwegian vertical farm business looking to expand by building new commercial farms that are within this size range (Apelthun, 2022). It should be noted that vertical farms can occur in smaller commercial spaces or larger (Avgoustaki, 2020b; Alpethun, 2022). The price per square meter for each space was identified by taking the price per square meter and averaging that across the 14 spaces.
AVERAGE_COST_PER_KW_PER_YEAR	.289	NOK/kW/Year	This is the average cost per kw per year. This value was determined by looking at the 2013 cost per kw (Statistics Norway, 2023f).
AVERAGE_COST_PER_L_PER_YEAR	0.01	NOK/Liter/Year	This parameter indicates the amount per liter water costs in Norway. This value was determined by looking at Statistics Norway (2023e) and identifying the cost of water per liter. The price of water was per 1000 Liters. This was then converted to the identified price.
AVERAGE_ENERGY_NEED	271.5	kW/(kilogram/year)	This is the indicated electricity use per kilogram of produce. This value is determined by taking the average energy requirement per kilogram of four key vertical farm produce (wheat, tomatoes, lettuce, and potatoes) (Kobayashi, 2022). This value provides a good representation of how much energy is used by a vertical farm.
AVERAGE_OPERATIONAL_COST_PER_FARM_PER_YEAR	109000	NOK/Year/Vertical Farm	This parameter showcases the indicated operational cost per farm per year. This showcases the yearly costs related to operations which include purchasing nutrients, packaging for produce, and seeds. This value was determined by Avgoustakis & Xydis, 2020a) in which they estimate the value of operational costs for a vertical farm in Denmark. The initial values were in euros and were then converted to 2013 NOK.
AVERAGE_PRICE_OF_IMPORTS	24	NOK/kilogram	This parameter indicates the price of imports per kilogram. This was found from market research from Index Box which showcased the 2022 price per ton in USD (2023). This was then converted to 2013 NOK value and then rounded. This price is used as a comparison to price per kilogram.
average_price_per_kilogram	Avg_cost_per_kg*PROFIT_MARGIN	NOK/kilogram	This is the average price per kilogram. It is determined by taking the profit margin and multiplying it by the average price per kilogram.
Avg_cost_per_kg	ENERGY_NEED_PER_KG_OF_PRODUCE_PE	NOK/kilogram	This parameter indicates the average cost per kilogram. It is determined by taking the average initial cost per kilogram from labor, water, and energy and adding them together.

	R_YEAR*AVERAGE_COST_PER_KW_PER_YEAR+ LABOR_NEED_PER_KG_OF_PRODUCE_PER_YEAR*AVERAGE_ANNUAL_SALARY_NORWAY+ WATER_NEED_PER_KG_OF_PRODUCE_PER_YEAR*AVERAGE_COST_PER_L_PER_YEAR+ Avg_operational_cost_per_kg		
Avg_operational_cost_per_kg	AVERAGE_OPERATIONAL_COST_PER_FARM_PER_YEAR/AVERAGE_OUTPUT_PER_VERTICAL_FARM	NOK/kilogram	This is the average operational cost per kilogram. It is determined by taking the average operation cost per farm per year and dividing it by average output per farm.
capital_investment	AVERAGE_CAPITAL_INVESTMENT*capital_investment_index	NOK/Vertical Farm	This is the amount of capital investment needed to build a vertical farm. It is determined by multiplying the capital investment index by the average capital investment.
capital_investment_index	MAX(EXP((cost_reduction_change_rate)*(TIME-STARTTIME)), MAX_COST_REDUCTION)	1	This variable indicates the rate at which capital investment decreases over time. It is determined by taking the exponent of cost reduction change rate multiplied by the number of years. A MAX function is included to indicate that costs will only decrease to a certain proportion of the average capital investment per farm. It is determined that costs will not increase indefinitely due to limitations on the economies of scale (Silberston, 1972). For instance, installation costs will only decrease to a certain amount due to limitations such as the specialization of labor. Specialization of labor, or improved knowledge of how to establish a vertical farm, will decrease to a certain amount as vertical farms reach optimal efficiency given the existing material. Additionally, the specialization of material made specifically for vertical

			farms, but only so much as material costs limit further decreases.
Completed_Vertical_Farms(t)	Completed_Vertical_Farms(t - dt) + (Completing_Vertical_Farms - Decaying_Vertical_Farms) * dt	Vertical Farm	The stock indicates the amount of completed vertical farms. It is determined by an increase from the inflow of completing vertical farms and the outflow of decaying vertical farms. Completing vertical farms transitions vertical farms from vertical farms under construction to completed vertical farms. The initial value of this stock is determined by initial completed vertical farms.
Completing_Vertical_Farms	Vertical_Farms_Under_Construction/COMPLETION_ADJUSTMENT_TIME	Vertical Farm/Years	This is the flow that transitions vertical farms from the stock of vertical farms under construction to the stock of completed vertical farms. This is the rate at which a vertical farm is constructed. It is determined by the division of the number of vertical farms under construction by the completion adjustment time.
COMPLETION_ADJUSTMENT_TIME	AVERAGE_COMPLETION_ADJUSTMENT_TIME*(1-SCENARIO_SWITCH_1) + (AVERAGE_COMPLETION_ADJUSTMENT_TIME+ALT_COMPLETION_ADJUSTMENT_TIME)*SCENARIO_SWITCH_1	year	This is the time it takes to complete a vertical farm. It is determined by the average completion adjustment time. It is impacted by Alternative Completion Adjustment Time which is turned on by the Scenario Switch 1.
Constructing_Vertical_Farms	(money_available_to_invest_in_vertical_farms/vertical_farm_investment)*vertical_farm_multiplier	Vertical Farm/Years	This is the inflow into the stock of vertical farms under construction. This indicates the rate of which farms begin construction. It is determined by the division of money available to invest in vertical farms and the capital expenses per vertical farm, and the multiplication of the vertical farm multiplier. As the sum of money available to invest in vertical farms increase, the more vertical farms could be built. However, this is limited by the vertical farm multiplier which indicates the number of vertical farms that could actually be built based on the number of vertical farms already established and the self-sufficiency gap. As the multiplier goes to zero, fewer farms can be built.
cost_per_kw_per_year	energy_cost_index*AVERAGE_COST_PER_KW_PER_YEAR	NOK/kW/Year	This variable determines the cost per kw per year. This is determined by multiplying the energy cost index by the average cost per kw per year.

cost_reduction_change_rate	INDICATED_COST_REDUCTION_CHANGE_RATE*effect_of_vertical_farm_ratio_to_cost_reduction_change_rate	1/year	This converter indicates how much costs will be reduced over time. It is determined by multiplying the indicated cost reduction change rate and the effect of vertical farm capacity to cost reduction change rate. As the effect increases, so too will the cost reduction. It is assumed that capital investment, operational costs, and energy costs will decrease by the same proportion as the actual amounts of decrease is uncertain. As such, the reduction of costs will be shared equally among these three variables. Labor costs and water costs were determined to not decrease as these prices are determined outside of the actual production process and these vertical farms are already running close to maximum efficacy in both domains as vertical farms recycle close to 100 percent of the water it uses and the technology already makes growing and harvesting very efficient (Avgoustakis & Xydis, 2020b).
DECAY_ADJUSTMENT_TIME	30	Year	This is an assumed time that vertical farms last. Avgoustakis and Xydis (2020a) performed an analysis between different greenhouse and vertical farm scenarios where they defined the effective payback period as 20 years. They do assume that farms will remain profitable, and thus still produce, after that 20 year period. As such, I am assuming that most farms last 30 years, however since the vertical farm industry is still nascent, I do not know the exact length of time most farms last. Further data collection is needed to provide a more accurate time.
Decaying_Vertical_Farms	Completed_Vertical_Farms/DECAY_ADJUSTMENT_TIME	Vertical Farm/Years	Decaying vertical farms is the outflow from the stock of completed vertical farms. It is determined by the number of completed vertical farms divided by the decay adjustment time. This is the rate at which completed vertical farms are no longer usable.
effect_of_ratio_of_price_per_kilogram_to_price_of_imports_on_fraction_of_demand_for_vertical_farm_produce	ratio_of_price_per_kilogram_to_price_of_imports^SENSITIVITY_OF_EFFECT_OF_RATIO_OF_PRICE_PER_KILOGRAM_TO_PRICE_OF_IMPORTS_ON_FRACTION_OF_DEMAND_FOR_VERTICAL_FARM_PRODUCE	1	This variable represents the amount of change in fraction of demand as a result in changes to the ratio of price per kilogram to import prices. When the ratio of price per kilogram to imports is greater than one, the fraction of demand will decreasingly decrease as it is undesirable to purchase a more expensive produce, but some distributors will still purchase in spite of price of vertical farms. However, if the ratio falls below one, the fraction of demand will increase increasingly as it becomes increasingly desirable to purchase vertical farm produce based on the price. At the ratio of one, there is an equal desire either for vertical farm produce or the price of imports.

			
effect_of_vertical_farm_ratio_to_cost_reduction_change_rate	ratio_of_vertical_farm_to_initial_vertical_farm^ SENSITIVITY_OF_RATIO_OF_VERTICAL_FARM_CAPACITY_ON_COST_REDUCTION_CHANGE_RATE	1	This effect shows how the increase in the ration of vertical farms to initial vertical farms impacts the cost reduction change rate. When this ratio exceeds one, the cost reduction change rate will increase decreasingly. This indicates that costs will decrease but less-than-proportional as it is difficult to reduce costs even if the industry is growing bigger and more powerful in finding ways to be more efficient. Meanwhile, with a ratio of less than one, the cost reduction change rate will increasingly decrease. As the industry grows smaller, it will have less power and ability to reduce costs. This effect is implemented to help explain the influence of the economies of scale in which as the larger of the scale of output, the lower the costs will be (Silberston, 1972). 
energy_cost	energy_use*cost_per_kw_per_year	NOK/Year	Energy cost is the total cost per year of vertical farm production. It assumes a collective cost for all vertical farms.

			This value is determined by the energy use multiplied by the cost per kw per year.
energy_cost_index	MAX(EXP((cost_reduction_change_rate)*(TIME-STARTTIME)), MAX_COST_REDUCTION)	1	This variable showcases how much the cost per kw per year will decrease over time. This is determined by taking the exponent of the cost reduction change rate multiplied by the number of years. A MAX function is included to indicate that costs will only decrease to a certain proportion of the average cost per kw per year. Energy costs are determined to be decreasing as a result improvements in LED Lighting. Up to 80 percent of electricity costs come from lighting (Kobayashi et al, 2022). It is also known that LEDs are becoming less expensive over time as the cost of production decreases and the efficacy of LEDs increase (Freeing Energy; Kobayashi, 2022). However, there are known limits to both the efficacy and the LED price decreases.
ENERGY_EFFICIENCY_BOOST	STEP(67.88, 2023)	kW/(kilogram/year)	This is the second policy which indicates that a hypothetical advancement in LED energy efficiency occurs. While there is skepticism in how efficient LEDs can become, there is still belief that it will occur (Zipkin, 2022; Kobayashi et al., 2022).
ENERGY_NEED_PER_KG_OF_PRODUCE_PER_YEAR	AVERAGE_ENERGY_NEED*(1-SWITCH:_ENERGY_EFFICIENCY) + (AVERAGE_ENERGY_NEED - ENERGY_EFFICIENCY_BOOST)*SWITCH:_ENERGY_EFFICIENCY	kW/(kilogram/year)	This is the indicated electricity use per kilogram of produce. This value is determined by taking the average energy requirement per kilogram of four key vertical farm produce (wheat, tomatoes, lettuce, and potatoes) (Kobayashi, 2022). This value provides a good representation of how much energy is used by a vertical farm.
energy_use	vertical_farm_production*ENERGY_NEED_PER_KG_OF_PRODUCE_PER_YEAR	kW	Energy use is the collective energy use of vertical farm production. This is determined by the multiplication of vertical farm production and the energy need per kilogram of produce per year.
FRACTION_OF_COST_REDUCTION_TO_CONSUMERS	0.3	1	This parameter determines how much of the cost reduction will go towards consumers. As costs reduce, vertical farms will lower their price per kilogram. However, these farms will not share reduce all of the cost reductions as the firms will look to keep some of those cost reductions for themselves as additional profit.

FRACTION_OF_PROFIT_REINVESTED	.8	1	This is an assumed value that determines the amount of vertical farm profits that are reinvested back into vertical farming. Since the goal is to establish more vertical farms, it is assumed that the majority of profits will be reinvested, but not all as it is the goal of the firm to save some of that money.
IMPORT_TAX	1+STEP(1.5, 2023)	1	This is an assumed value to indicate a proposed policy to increase the value on the price of imports.
INDICATED_COST_REDUCTION_CHANGE_RATE	-0.003	1/year	This is the indicated cost reduction change rate. This is an assumed value determined by hand calibration of the model to reflect an desired representation of the economies of scale.
INDICATED_SIZE_OF_VERTICAL_FARM	200	m2/Vertical Farm	This is an assumption that the indicated size of a vertical farm in Norway will be 200 meters squared. This was influenced by an existing Norwegian vertical farm business looking to expand by building new commercial farms that are within this size range (Apelthun, 2022). It should be noted that vertical farms can occur in smaller or larger commercial spaces (Avgoustaki, 2020b; Alpethun, 2022).
INITAL_VERTICAL_FARM_INVENTORY	192000	kilogram	This value was determined by undergoing hand calibration to get rid of transient behavior.
INITIAL_COMPLETED_VERTICAL_FARMS	50	Vertical Farm	This is the initial completed vertical farms. Data measuring vertical farms is still limited however for the initial value I use the assumption that the number of vertical farms in Norway is still small. I also have data that the number of commercial greenhouses in Norway are declining. In 2010, there were only 637 farms measured (Statistics Norway, 2013). It is assumed that vertical farms are a fraction of this number as there are known vertical farms in Norway, but the exact number is uncertain (Butturini & Marcelis, 2019).
INITIAL_VERTICAL_FARMS_UNDER_CONSTRUCTION	6	Vertical Farm	Initial vertical under construction farms is an assumed value. It is believed to be less than the initial number of completed farms and indicates the initial number of incomplete vertical farms under construction. The value was chosen as it reflects the rate of constructing vertical farms at the initial time.
labor_cost	labor_need*AVERAGE_ANNUAL_SALARY_NORWAY	NOK/year	Labor cost determines the collective labor cost for vertical farm produce production. It is determined by the multiplication of the labor need and average annual salary in Norway.
labor_need	LABOR_NEED_PER_KG_OF_PRODUCE_PER_YEAR*vertical_farm_production	Worker	Labor need is the collective need of laborers for the vertical farm produce production. It is determined by the labor need per kilogram of produce per year multiplied by the vertical farm production.

LABOR_NEED_PER_KG_OF_PRODUCE_PER_YEAR	0.000018	Worker/(kilogram/year)	This variable indicates the number of workers needed per kilogram of produce. This value is determined from Avgoustakis and Xydis (2020a) where they measure the amount of workers they need to produce a kilogram of produce. This provides a reasonable estimate as to how many workers it takes to manage a vertical farm based on the kilograms of produce.
MAX_COST_REDUCTION	0.7	1	This is parameter that assumes the maximum proportional reduction of the costs of energy, operations, and capital investment as well as the price per kilogram. This is an assumed value as it uncertain how much costs can actually be reduced, but it is know that costs cannot reduce forever due to limits of the economics of scale (Silberston, 1972). For instance, cost of material as a result of increasing the power of an industry to negotiate prices cannot be reduced indefinitely as prices can only go so low.
money_available_to_invest_in_vertical_farms	MAX(0, vertical_farm_profit*FRACTION_OF_PROFIT_REINVESTED+government_subsidies)	NOK/Year	This variable is the total pool of money made available to be invested in vertical farming. This is determined by the addition of vertical farm profit and by government subsidies. A MAX function is used to indicate that if the amount of money made available goes below zero, then there would be no money to invest in constructing vertical farms.
operational_cost	operational_cost_per_farm_per_year*Completed_Vertical_Farms	NOK/Year	This is the operational cost per year. This measures the total amount of costs it takes to operate all vertical farms in Norway. This includes the costs for maintenance as well as miscellaneous costs related to packaging, providing nutrients to the plants, and purchasing new seeds.
operational_cost_index	MAX(EXP((cost_reduction_change_rate)*(TIME-STARTTIME)), MAX_COST_REDUCTION)	1	This variable indicates the rate at which operational costs decrease over time. It is determined by taking the exponent of cost reduction change rate multiplied by the number of years. A MAX function is included to indicate that costs will only decrease to a certain proportion of the average operational cost per farm per year. It is determined that costs will not increase indefinitely due to limitations on the economies of scale (Silberston, 1972). For instance, the costs related to nutrients, packaging, and seeds cannot decrease indefinitely due to cost limits within their respective supply chains. However, costs are expected to decrease in part due to further specialization of the vertical farm. Silberston (1972) describes that as a plant, or in this case a vertical farm, begins to produce more and establishes itself, it can bring down operating cost per unit as production becomes more consistent and as the specialized knowledge of the farm will increase over time to improve its efficiency.

operational_cost_per_farm_per_year	AVERAGE_OPERATIONAL_COST_PER_FARM_PER_YEAR*operational_cost_index	NOK/Year/Vertical Farm	This variable determines the operational cost per farm per year. It is determined by multiplying the average operational cost per farm per year by the operational cost index.
PRICE_OF_IMPORTS	AVERAGE_PRICE_OF_IMPORTS*IMPORT_TAX*SWITCH:_IMPORT_TAX + AVERAGE_PRICE_OF_IMPORTS*(1-SWITCH:_IMPORT_TAX)	NOK/Kilogram	This is the price of imports but it is also impacted by import tax and a switch. These additional parameters are used for policy testing.
price_per_kilogram	average_price_per_kilogram*price_per_kilogram_index	NOK/kilogram	This is the typical price per kilogram of vertical farm produce. This is determined by multiplying the average price per kilogram by the price per kiloogram index. This value provides a good assessment of price as vertical farm goods are viewed as a higher quality item relative to non-vertical farm goods but also more expensive due to the production costs (Zipkin, 2022). It is assumed that as vertical farms reduce their expenses over time, a fraction of those cost reductions will go to lowering price per kilogram.
price_per_kilogram_index	MAX(EXP((cost_reduction_change_rate*FRACTION_OF_COST_REDUCTION_TO_CONSUMERS)*(TIME-STARTTIME)), MAX_COST_REDUCTION)	1	This index indicates that a fraction of the cost reduction change rate will impact price per kilogram over time. This is determined by taking the exponent of fraction of cost reduction to consumers multiplied by the cost reduction change rate and the year to see how much the price per kilogram is reduced over time. A MAX function is included so that price per kilogram will not decrease forever. If price per kilogram index falls below max cost reduction rate, then the price per kilogram will maintain the proportion of the price as determined by max cost reduction.
PROFIT_MARGIN	1.2	1	This is a desired profit margin. It is assumed that the typical vertical farm will want to make a 20 percent profit on each kilogram sold.
ratio_of_price_per_kilogram_to_price_of_imports	price_per_kilogram/PRICE_OF_IMPORTS	1	This variable indicates the ratio between vertical farm price per kilogram to the price per kilogram of imports. This done by taking the price per kilogram and dividing that by price of imports.
ratio_of_vertical_farm_to_initial_vertical_farm	Completed_Vertical_Farms/INIT	1	This converter is the ratio of vertical farm to initial vertical farm. This is meant to represent how much the vertical farm

	(Completed_Vertical_Farms)		industry has grown in relation to the initial size by measure the number of vertical farms in proportion to the initial.
real_estate_expense	AVERAGE_COST_OF_COMMERCIAL_SPACE*INDICATED_SIZE_OF_VERTICAL_FARM	NOK/Vertical Farm	This is a variable that shows the assumed cost to purchase the real estate needed to begin construction of a new vertical farm. It includes the assumption from indicated size of vertical farm that a farm is 250 meters squared and that the cost per meter squared is 27,328 NOK as determined in average cost of commercial space.
revenue	Shipment_to_Distributors*price_per_kilogram	NOK/Year	Revenue is the collective money generated by the consumption of vertical farm produce. This is found by looking at the actual demand of vertical farm produce in shipment to distributors multiplied by the price per kilogram.
SCENARIO_SWITCH_1	0	1	This is a switch variable that turns on and off the Alternative Completion Adjustment Time Scenario.
SENSITIVITY_OF_EFFECT_OF_RATIO_OF_PRICE_PER_KILOGRAM_TO_PRICE_OF_IMPORTS_ON_FRACTION_OF_DEMAND_FOR_VERTICAL_FARM_PRODUCE	-1	1	This parameter indicates the sensitivity of fraction of demand for vertical farm produce from changes in the ratio of vertical farm produce price to import price. It is assumed in this model that there is disproportionate reaction in fraction of demand to changes in the ratio. As the ratio between price per kilogram to price of imports increases, it is less likely that distributors will order from the vertical farms. In other words, the fraction of demand will decrease. Meanwhile, as the ratio decreases, it is more likely that distributors will order from vertical farms, or the fraction of demand will increase.
SENSITIVITY_OF_RATIO_OF_VERTICAL_FARM_CAPACITY_ON_COST_REDUCTION_CHANGE_RATE	0.3	1	This parameter determines the sensitivity in cost reduction from changes in ratio of vertical farm to initial vertical farms. It is assumed that cost reduction is relatively inelastic to changes in this ratio which means that as this ratio increases, cost reduction will increase decreasingly. This is meant to reflect an economies of scale impact. Economies of scale is a measure that showcases that as a firm, or in this case an industry, grows larger the costs of production will decrease at larger scales of output (Silberston, 1972). In this model, as the number of vertical farms increase in relation to the initial number, the average costs are lower both to produce vertical farms and the production of produce within those vertical farms.
SWITCH:_ENERGY_EFFICIENCY	0	1	This is a switch between one and zero that will be used for policy testing of the introduction of an import tax. The Switch is turned on with a value of 1. It is off with a value of 0.
SWITCH:_IMPORT_TAX	0	1	This is a switch between one and zero that will be used for policy testing of the introduction of an import tax. The

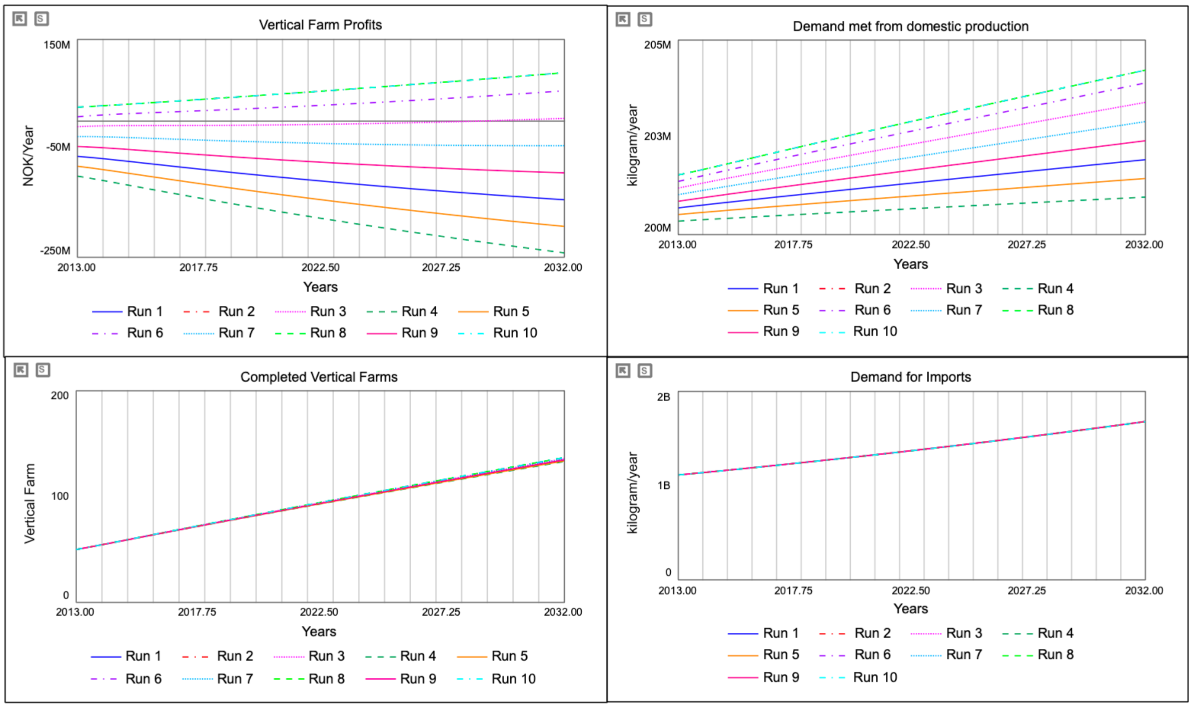
			Switch is turned on with a value of 1. It is off with a value of 0.
vertical_farm_investment	real_estate_expense+capital_investment	NOK/Vertical Farm	This variable determines the total amount of investment needed to establish one vertical farm. This found by adding the capital investment by the real estate expense.
vertical_farm_multiplier	(1-vertical_farm_capacity)*"self-sufficiency_gap"	1	This is the vertical farm multiplier which determines the fraction of vertical farms to build. This is based on vertical farm capacity and the self sufficiency gap. As vertical farm capacity reaches 1, or full capacity, there is less incentive to build farms. Therefore, as capacity gets larger, the multiplier gets smaller so that less farms are built. However, this is not the only indicator of wanting to build farms. Self-sufficiency gap also indicates the number of farms that should be built. As this gap grows, there is more incentive to build. As it shrinks, there is less incentive. Together, they determine the fraction of vertical farms that should be built.
vertical_farm_profit	revenue-(labor_cost+energy_cost+water_cost+operational_cost)	NOK/Year	Vertical farm profit showcases the amount of money generated from vertical farm production. This is determined by the revenue generated subtracted by the sum costs.
Vertical_Farms_Under_Construction(t)	Vertical_Farms_Under_Construction(t - dt) + (Constructing_Vertical_Farms - Completing_Vertical_Farms) * dt	Vertical Farm	The stock of vertical farms under construction is the number of vertical farms being built. It is increased by the inflow of constructing vertical farms and decreased by the flow of completing vertical farms. Its initial value is determined by initial vertical farms under construction.
water_cost	water_use*AVERAGE_COST_PER_L_PER_YEAR	NOK/Year	The water cost is the collective water expense of production. It is determined by the multiplication of water use and average cost per liter per year.
WATER_NEED_PER_KG_OF_PRODUCE_PER_YEAR	17	Liter/(kilogram/year)	This parameter indicates the amount of water needed per kilogram of produce. This is based on evidence provided by Song et al (2020) in which they measure the typical water usage of vertical farm produce. This of course can vary based on the produce type.
water_use	vertical_farm_production*WATER_NEED_PER_KG_OF_PRODUCE_PER_YEAR	Liter	This variable showcases the collective amount of water used during production each year. This is found by multiplying the vertical farm production by the water need per kilogram of produce per year.

Appendix C: Sensitivity Analysis

For this model, all parameters were tested that did not have completely verified information were tested on the base scenario. Parameters were tested using Stella's sensitivity analysis tool using Latin Hypercube with six runs and uniform sampling. I have inserted a table that showcases all the parameters that were tested and the sensitivity of those parameters.

Model Sector	Parameter	Range	Sensitivity
Vertical Farming Finances	Sensitivity of ratio of vertical farm capacity on cost reduction change rate	0.15-0.45	Not Sensitive
	Indicated cost reduction change rate	(-0.0045)-(-0.0015)	Numerical
	Profit Margin	1-1.8	Numerical
	Fraction of cost reduction to consumers	0.15-0.45	Not Sensitive
	Max cost reduction	0.35-1	Not Sensitive
	Average price of imports	12-90	Behavioral
	Sensitivity of effect of ratio of price per kilogram to price of imports on fraction of demand for vertical farm produce	(-1.5)-(-.5)	Numerical
	Average energy need	136-408	Numerical
	Labor need per kilogram of produce per year	0.00009-0.000027	Not Sensitive
	Water need per kg of produce per year	8.5-25.5	Not Sensitive
	Average operational cost per farm per year	54500-163500	Not Sensitive
	Average cost per L per year	0.005-0.015	Not Sensitive
	Average annual salary Norway	190000-570000	Not Sensitive
	Average cost per kw per year	0.15-0.45	Numerical
	Average capital investment	862500000-287500000	Numerical
	Average cost of commercial space	13664-40992	Not Sensitive
	Indicated size of vertical farm	100-300	Not Sensitive
	Fraction of proift reinvested	0.4-1	Not Sensitive
	Average completion adjustment time	0.5-5	Behavioral
	Initial vertical farms under construction	0-12	Numerical
	Initial completed vertical farms	25-75	Numerical
	Initial vertical farm inventory	96000-288000	Not Sensitive
	Decay adjustment time	15-45	Numerical
Government Subsidies Sector	Desired self-sufficiency	0.5-1	Numerical
	Inflection Point	0.25-0.75	Numerical
	Steepness	2.5-7.5	Numerical
	Government subsidies to agriculture change rate	0.0035-0.0105	Not Sensitive
	Indicated fraction of subsidies to vertical farms per year	0.15-0.45	Numerical
Food Supply	Average output per vertical farm	15500-46500	Numerical
	Food waste rate	0.0025-0.0075	Not Sensitive
	Demand fulfilled from conventional farms Norway	100000000-300000000	Numerical
	Supply coverage	1.0-2.0	Numerical
Food Demand	Birth fraction	0.006-0.018	Not Sensitive
	Death fraction	0.004-0.012	Not Sensitive
	Reference net migration fraction	0.004-0.012	Not Sensitive
	Per capita consumption change rate	0.0035-0.0105	Not Sensitive
	Reference per capita consumption	130-390	Numerical

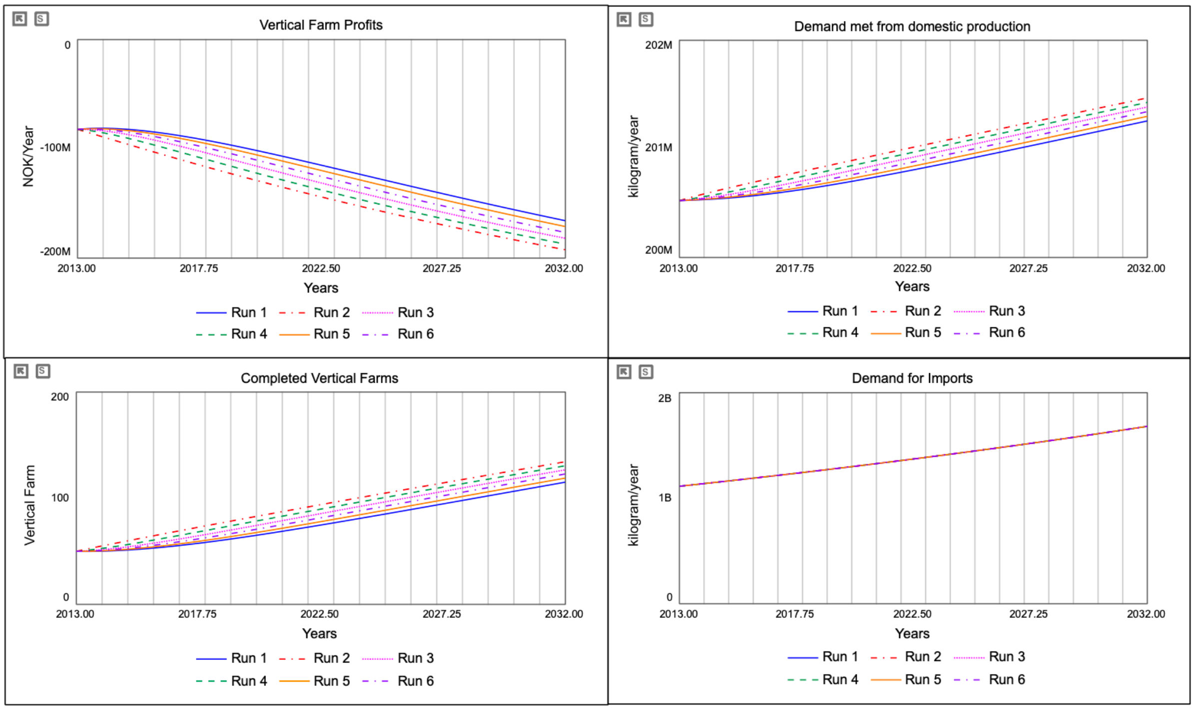
Average price of imports



Looking first at average price of imports, this variable shows significant behavioral sensitivity and I use this in my policy analysis as a leverage point. The shift in behavior is seen in the KPI profits in which profits is decreasing decreasingly initially. When average price of imports increases above 89, the price per kilogram, profits increase increasingly. While the other KPIs do not reflect this shift in behavior, demand met from domestic production does showcase significant numerical sensitivity. The amount of demand increasingly increases as average price of imports increases.

This behavior in profits shifts as due to a change of strength of *Price Comparison (R5).* As the average price of imports increases, this decreases the ratio of price per kilogram to price of imports to one. As this ratio decreases, there is a stronger demand for vertical farm produce. This increased demand, leads to more orders, increased revenue, increased profits, driving down the price per kilogram through the economies of scale, and further reducing the ratio. Once price per kilogram is less than average price of imports, profits go above zero and demand met from domestic production is at its highest. There are nominal impacts on the number of vertical farms and demand for imports. This provides insight that the government subsidies loops play a significant role in determining the number of vertical farms as the number of vertical farms are increasing whether profits are positive or negative, and production from vertical farms is still not large enough to impact the demand for imports. Demand for imports is being driven by an exogenous population which increases food demand faster than vertical farms can match it.

Average completion adjustment time



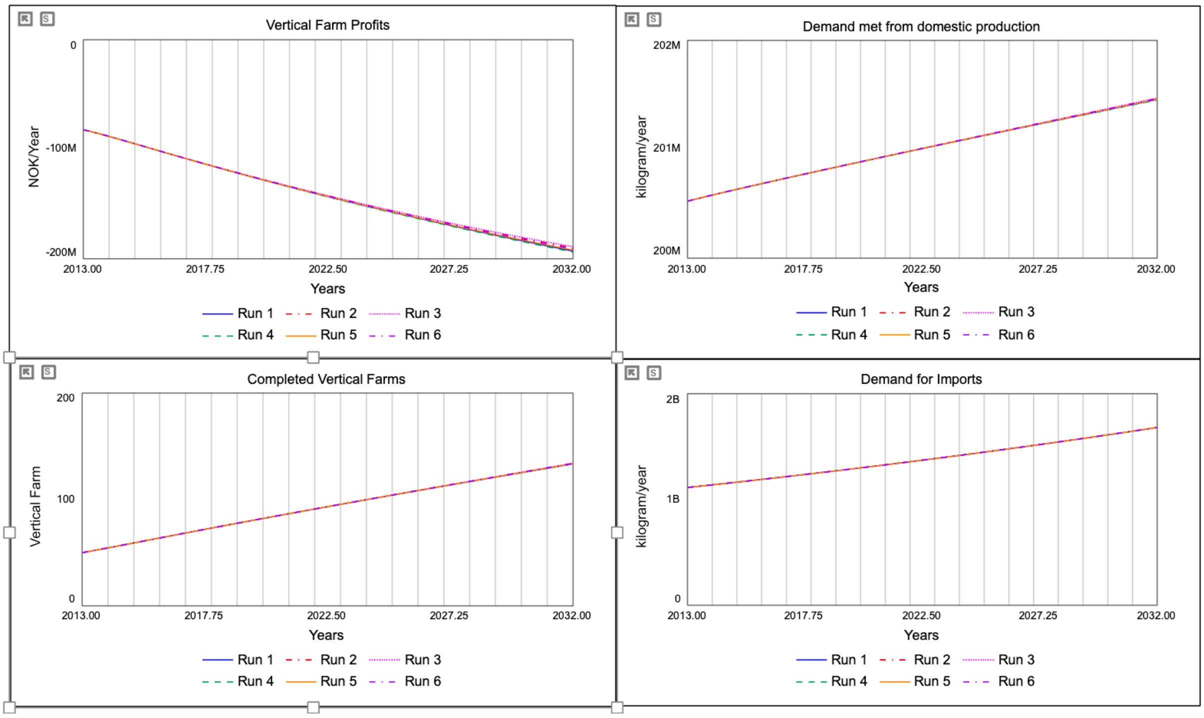
Next, average completion adjustment time shows a slight behavioral change. As described in the base run analysis, loops *Maturing Vertical Farms (B1)* and *Decay of Vertical Farms (B3)* are often dominant in this model. They are limits on the construction and implementation of vertical farms. By changing the completion adjustment time, these two loops are impacted. As the adjustment time increases, a larger delay occurs in which vertical farms under construction are shifted to completed vertical farms.

This is seen in the KPI completed vertical farms in which a large adjustment time leads to a longer stagnation before normal behavior of increasingly increasing number of vertical farms occur. Meanwhile, profits are higher, or less negative, as there are fewer vertical farms due to the delay. There is less produce production due to fewer farms and there are fewer expenses as a result.

Similarly, demand met from domestic production is met less quickly when there is a higher delay as there are fewer vertical farms producing goods. This occurs as seen in loop *Making the Money (R1),* where the carrying capacity for vertical farms remains low and does not drive demand for vertical farm produce as a lower adjustment time would.

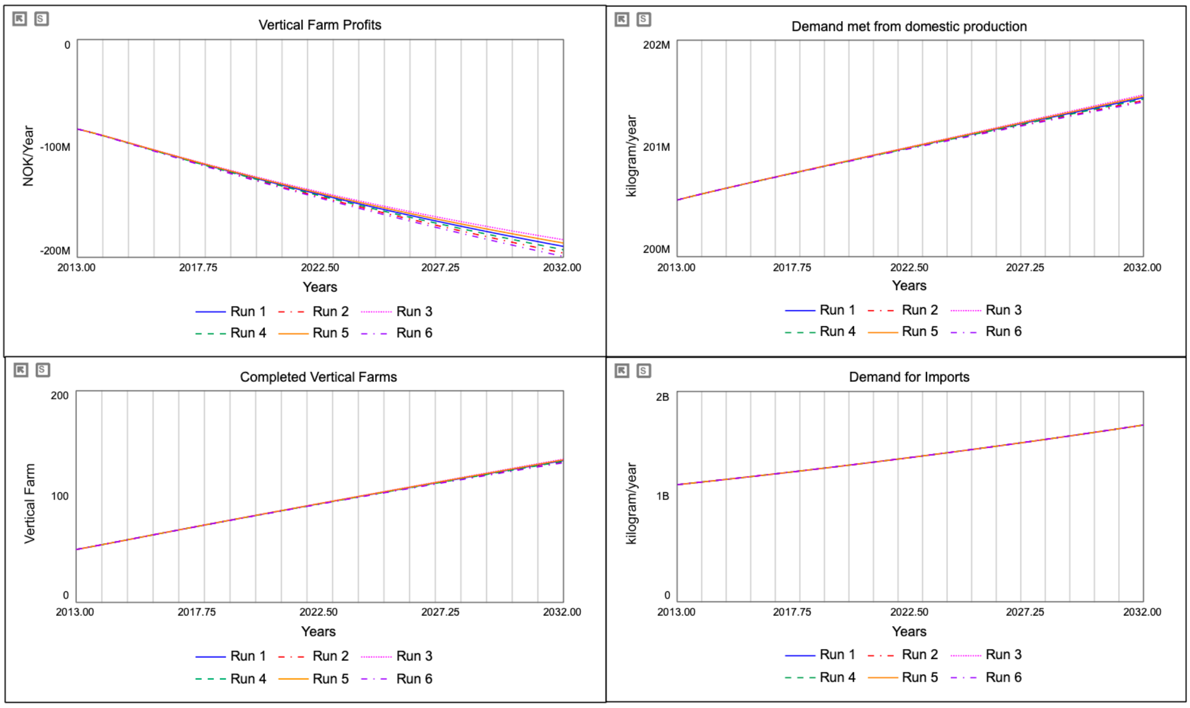
Meanwhile, the demand for imports is not impacted due to population growth and an ever-increasing demand for plant produce that cannot be met by vertical farms.

Sensitivity of ratio of vertical farm capacity on cost reduction change rate



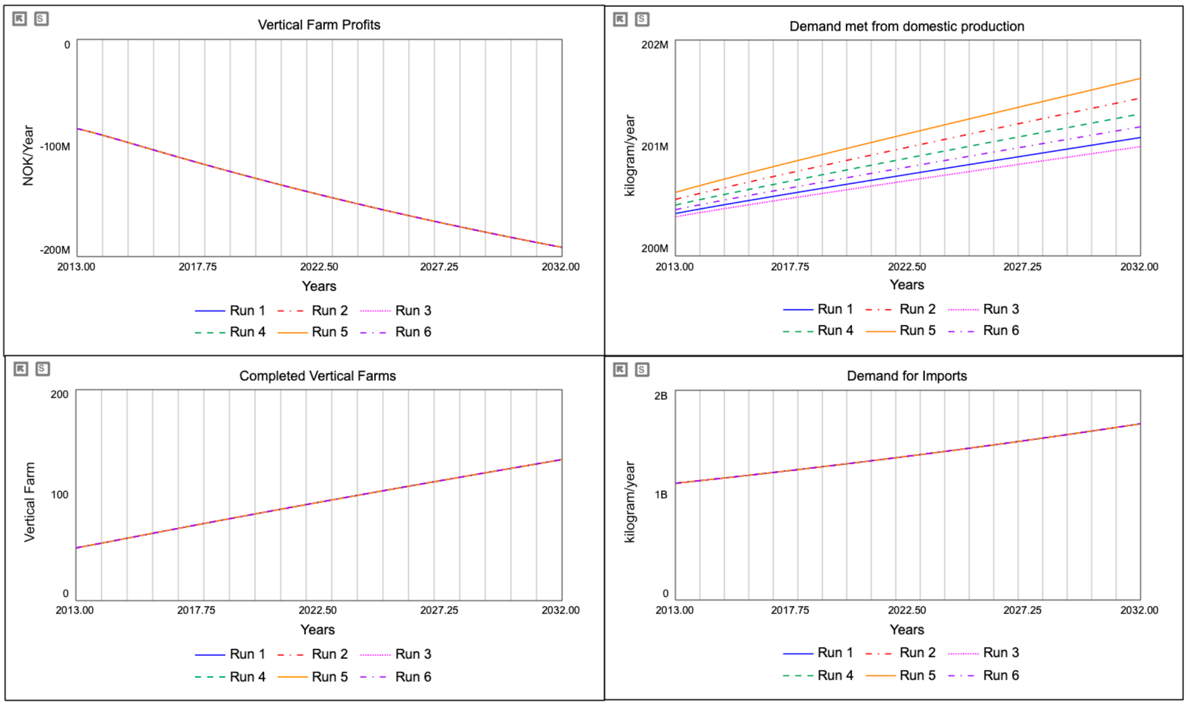
I first want to provide an example of a variable that is not sensitive to showcase I view a not sensitive parameter. Regardless of what value sensitivity of ratio of vertical farm capacity on cost reduction change rate, the model does not react. A change in this parameter, and parameters like it, do not cause significant change in the model behavior. The following parameters are those that showcase visible change in model sensitivity and are worthwhile delving into to understand the impacts.

Indicated Cost Reduction Change Rate



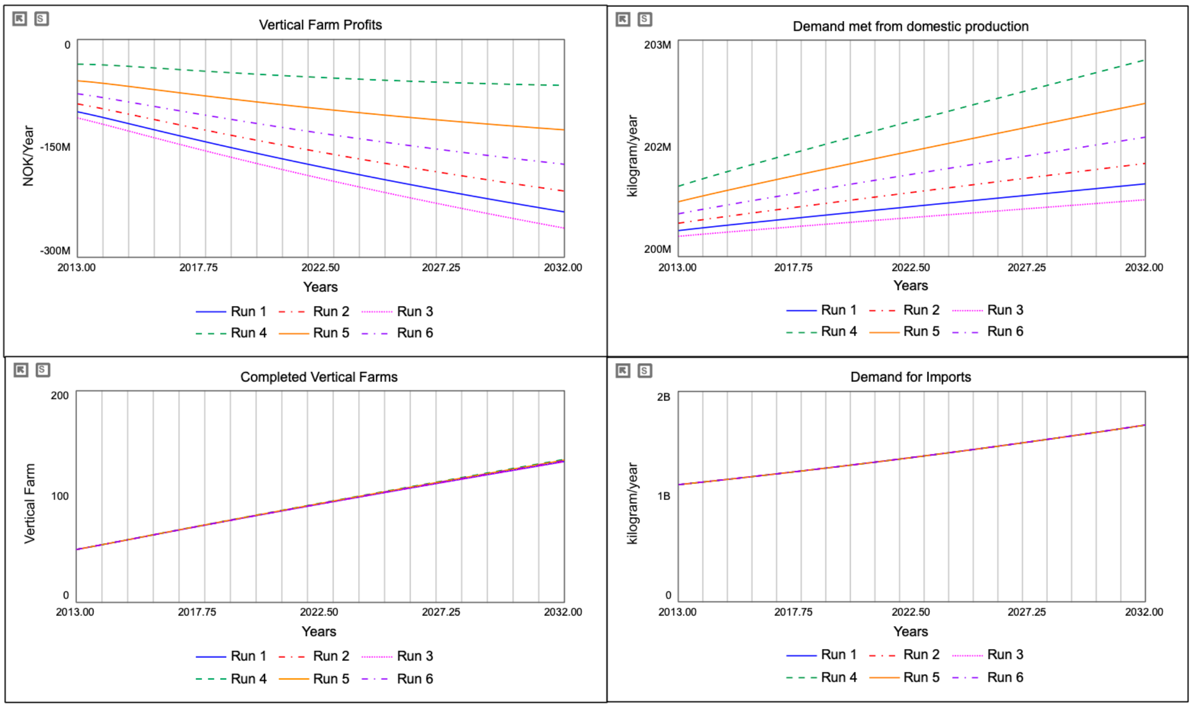
Indicated cost reduction change rate is numerically sensitive, albeit very slightly. This variable impacts the economies of scale loops. It is multiplied by the effect of vertical farm ratio to cost reduction change rate to determine how much costs are reduced for loops *Saving on the Set Up (R2), Numbing the Shock (R3),* and *Working Smarter (R4)* as well as how much price per kilogram is reduced in loop *Price Comparison (R5).* The KPI that shows the sensitivity is vertical farm profits. As this change rate gets larger, profit increases as the capital, energy, and operational expenses are reduced in the reinforcing loops mentioned. This spurns further vertical farm construction and further cost reduction. Meanwhile, as price per kilogram decreases, it triggers further demand for vertical farm produce which increases revenue and profits and leads to more vertical farm growth. This leads to a slight uptick in more demand met from domestic produce as this change rate gets larger. There are also small increases seen in completed vertical farms, but, again, this variable showcases that the model is only slightly sensitive towards it.

Profit Margin



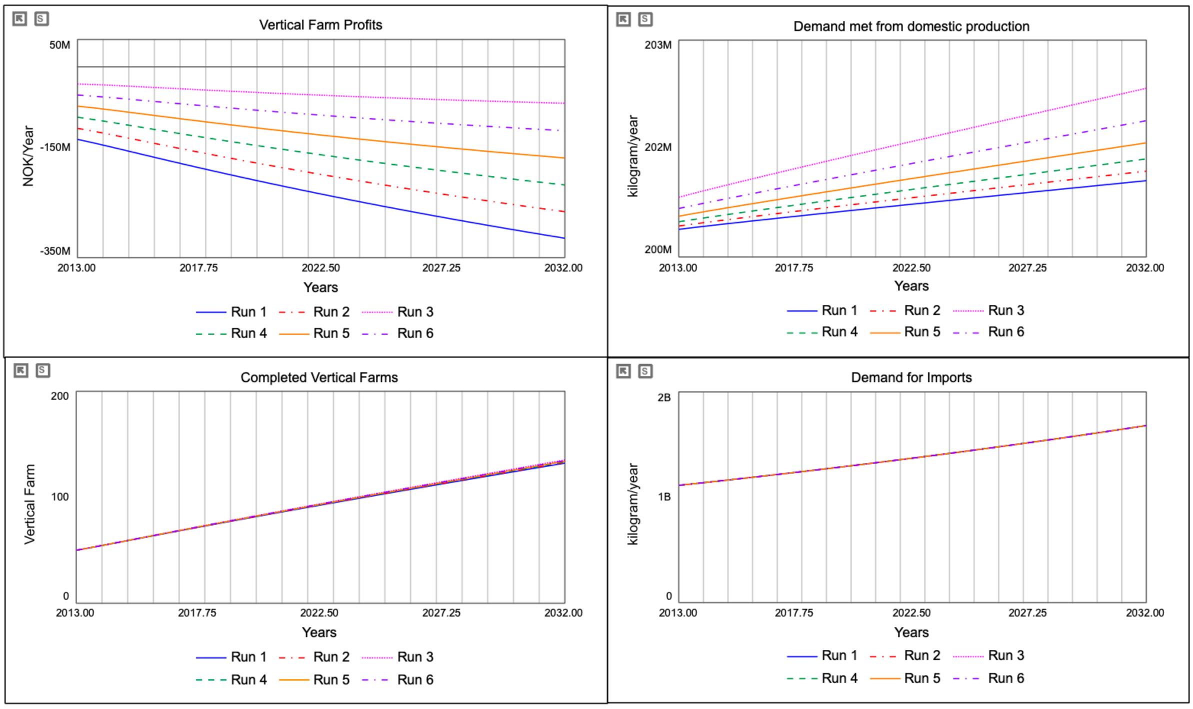
This variable indicates that this model is numerically sensitive. However, this is seen only in the KPI demand met from domestic production. As profit margin increases, this generates a lower demand met from domestic produce due to the rise in price per kilogram. As this price per kilogram increases, there is smaller desire to meet the demand from vertical farms. This lowers revenue and would prevent further vertical farm construction. However, since the price per kilogram is already high in relation to imports, the other loops and the other KPIs are not impacted as demand for vertical farm produce is already low.

Sensitivity of effect of ratio of price per kilogram to price of imports on fraction of demand for vertical farm produce



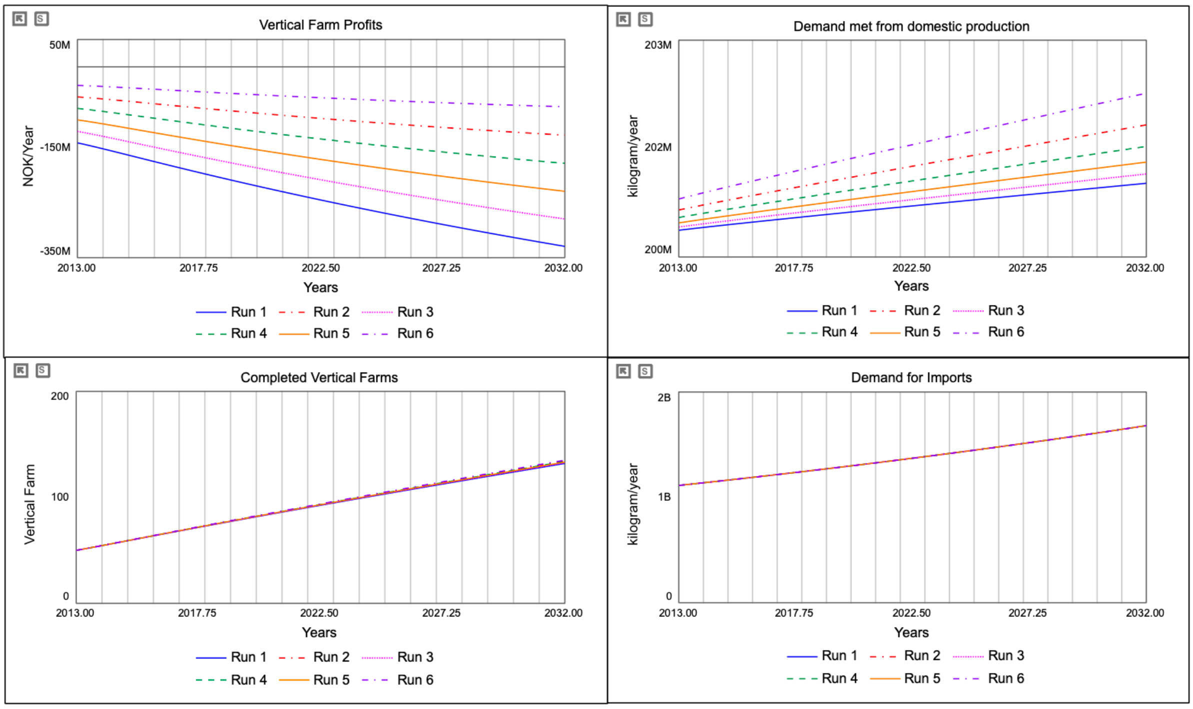
This model is numerically sensitive to this variable. The KPIs vertical farm profits and demand met from domestic production showcase this most clearly. This means that when the value is higher, demand is less sensitive to price per kilogram. As such, these KPIs show that when this variable is at its highest, or is closer to zero, there is more demand for domestic produce. This leads to higher revenues and profits. This leads to further vertical farm production, which is not showcased here as profits remain negative and vertical farms are being built more so from government subsidies. Yet, further farm production leads to reduced prices due to economies of scale which further reduces the price driving demand for vertical farm produce. This showcases the behavior as seen in profits and demand met from domestic production.

Energy need



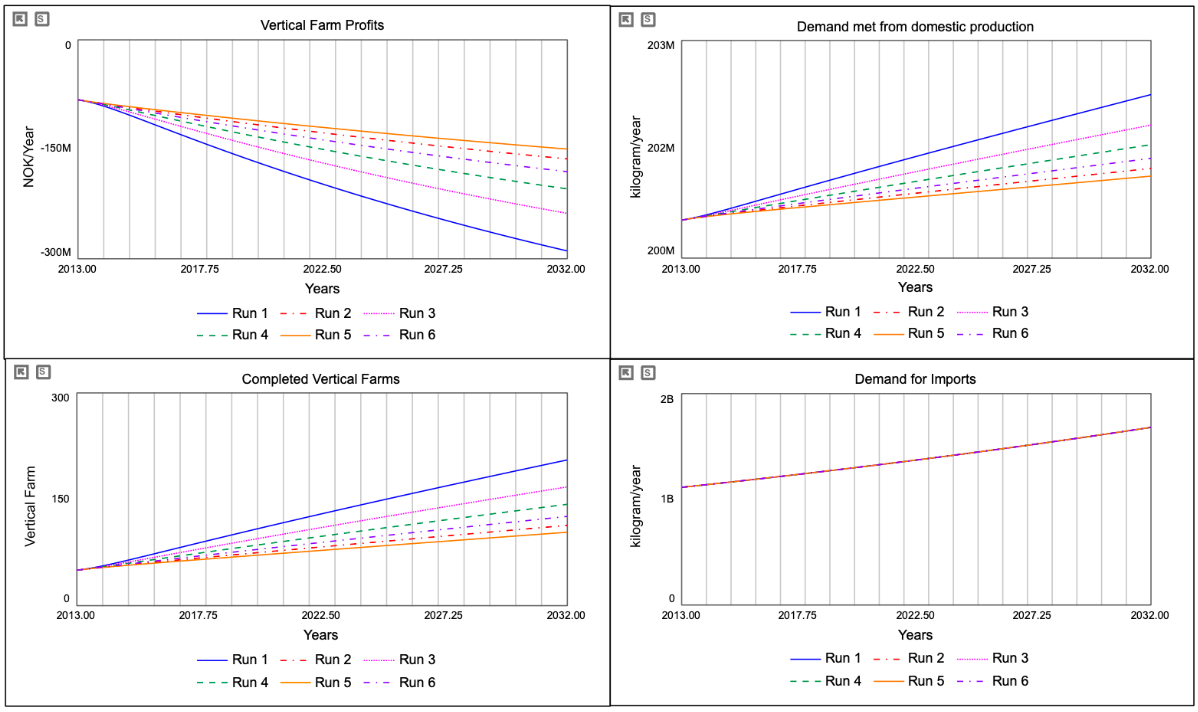
This model is numerically to energy need. This is seen most notably in vertical farm profits and demand met from vertical farm production. As energy need is reduced, the higher the profits and the higher the demand for vertical farm produce. We also see a miniscule increase in the number of completed farms. As energy need is reduced, it impacts loop *B2* by weakening it. By reducing the need, energy costs are reduced which improves profit margins. While subsides lead the way in terms of funding vertical farm construction, improved profit margins lead to more vertical farms which increases vertical farm capacity and leads to further demand for vertical farm produce. As such, demand met from domestic production increases significantly as energy need is reduced. Congruently, a lower need leads to a lower price per kilogram as the price per kilogram is determined by the average costs multiplied by average need. This also drives demand.

Average cost per kw per year



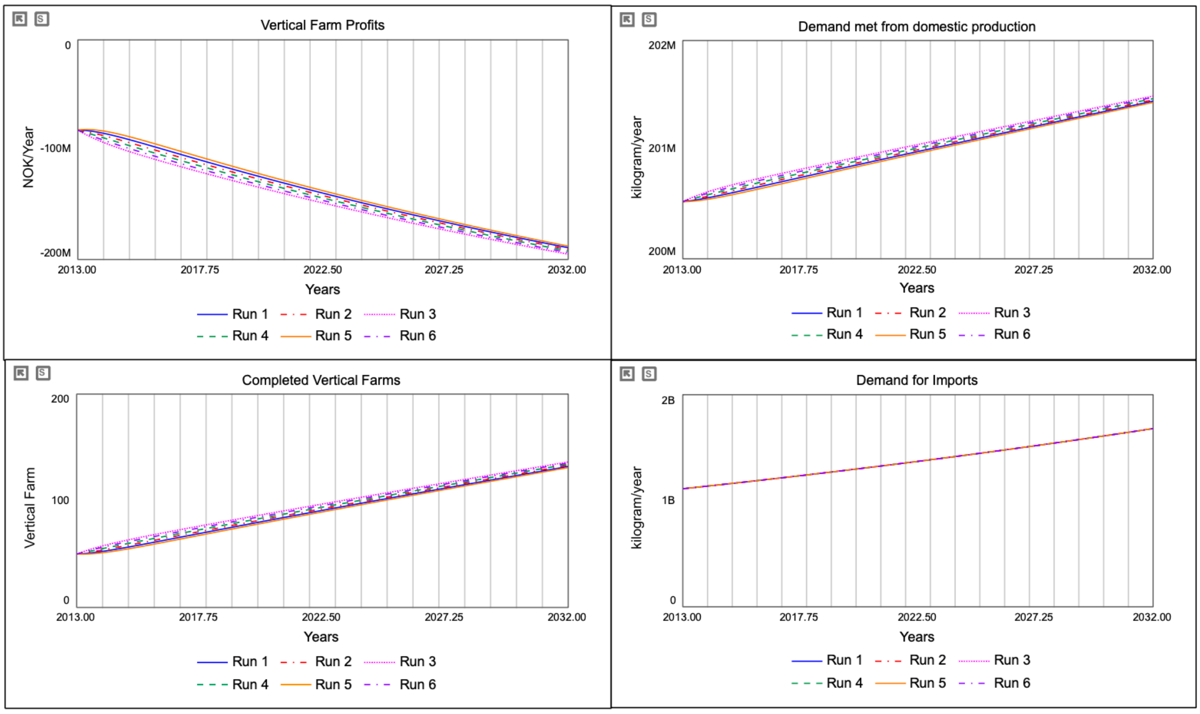
Much like energy need, this variable showcases numerical sensitivity through the KPIs of vertical farm profits and demand met from domestic production. As the cost per kw is lowered, the profits increase and so too does demand from domestic production. This occurs as the loop *B2* is weakened. This allows for more completed vertical farms which can be seen in slight changes to completed vertical farms KPI. This further improves the demand for vertical farm produce and the demand met from domestic production. Revenues are also increased in loop *R1* as more demand leads to more revenue which further improves profits. Congruently, a lower cost leads to a lower price per kilogram as the price per kilogram is determined by the average costs. This also drives demand.

Average capital investment



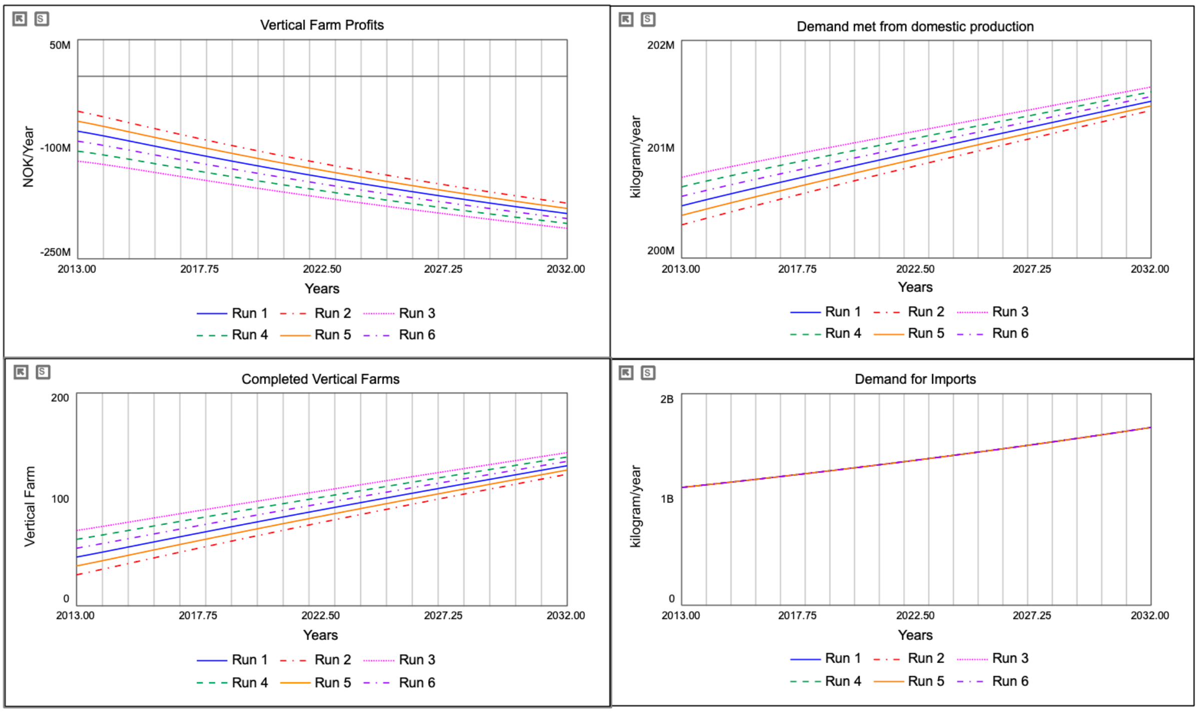
Average capital investment indicates significant numerical sensitivity. As the capital investment per vertical farm decreases, this leads to more vertical farm production as the amount it takes to build a farm lessens. The more vertical farms lead to more plant produce production which increases costs significantly. This leads to a larger decline of profits as capital investment decreases. Meanwhile, demand met from domestic production increases as there are more vertical farms. With more farms, there is a larger capacity. With a larger capacity, demand surges. However, due to the price per kilogram being higher than import prices, there are still limits to how much demand will rise. This limits the revenues which also prevents profits from increasing.

Initial vertical farms under construction



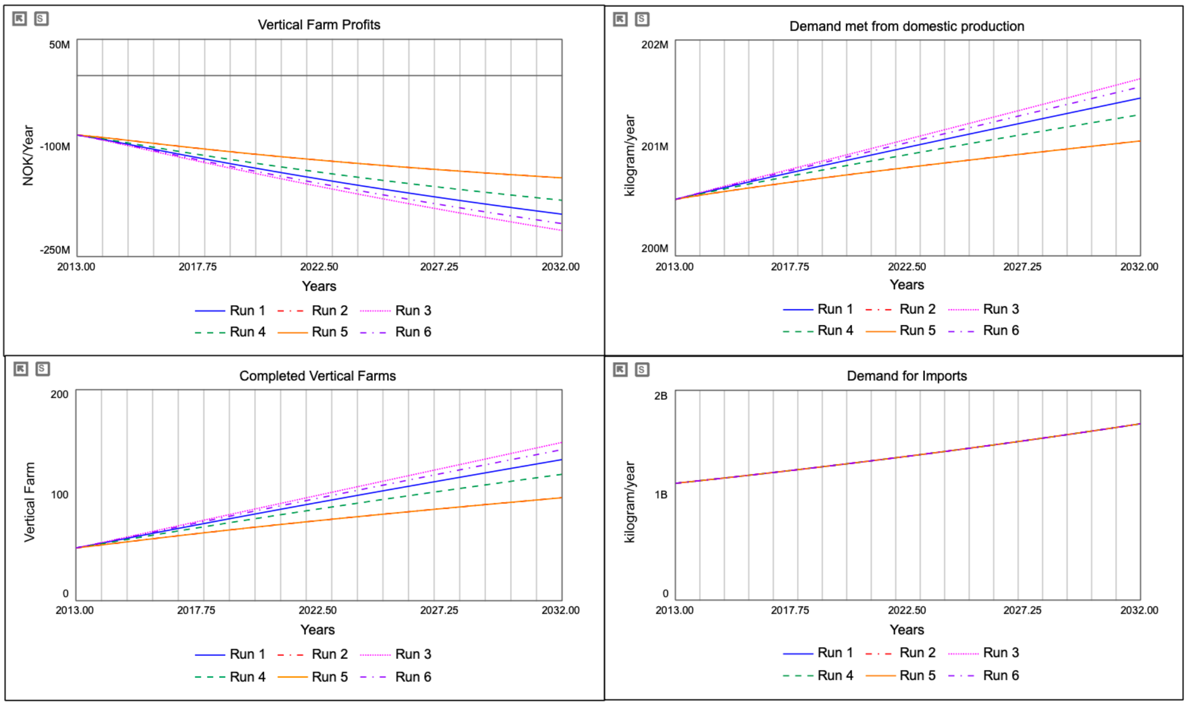
Initial vertical farm construction has a small numerical sensitivity on the model. With no farms under construction there is a delay as to when completed vertical farms increase. As this value gets higher, completed vertical farms increase respectively. For similar reasons, profits decline with a delay when initial farms under construction are zero. The same is for when demand met from domestic production. With a delay in completed vertical farms due to the need to start building farms and then to complete them, capacity does not increase preventing demand from increasing initially. Meanwhile, with no new farms, there is no new produce production which means expenses do not start increasing. However, when initial vertical farms under construction are higher, demand met from domestic production increases more quickly, albeit still with a delay due to the need to complete vertical farms. The same applies to profits.

Initial completed vertical farms



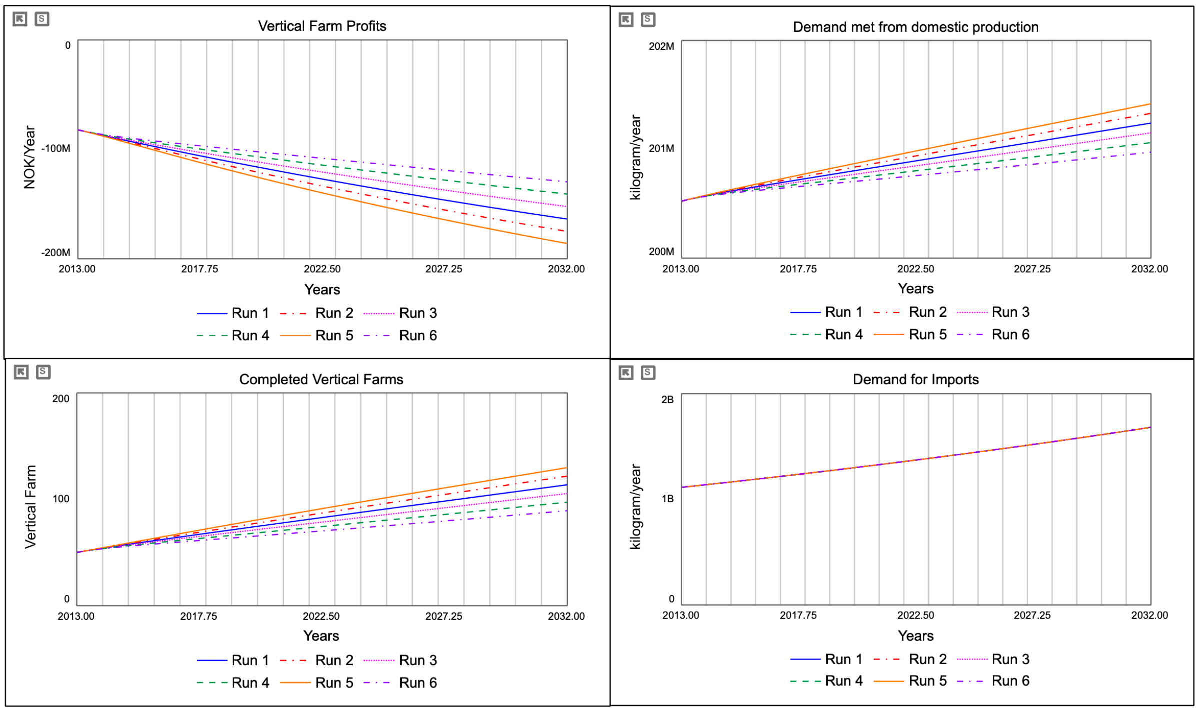
The model is numerically sensitive to initial completed vertical farms. This can be seen in the KPIs of vertical farm profits, demand met from domestic production, and from completed vertical farms. As there is a higher initial number of vertical farms, profits decrease. With more farms, they produce more but, in doing so, increase the expenses. Since price per kilogram is greater than price of imports, demand for vertical farm produce will increase as vertical farm capacity is increased with more vertical farms, but not enough for the revenue generated from the new demand to offset profits. As such, we see numerical change, but not a change in behavior.

Decay adjustment time



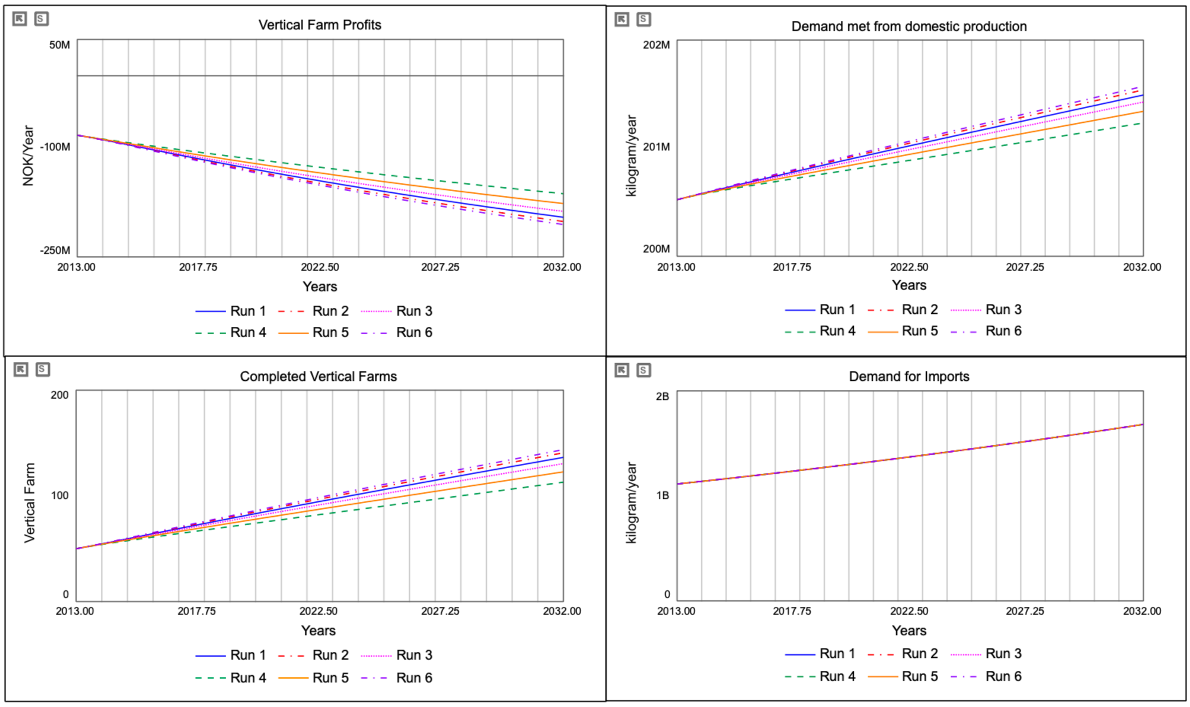
The model is numerically sensitive to decay adjustment time. This variable indicates how quickly completed vertical farms decay and go into disuse. Vertical farm profits show that when the decay time is smaller, meaning farms decay more quickly, profits are higher. With fewer farms in operation, there is less overall production and fewer overall costs as a result. Comparatively, completed vertical farms and demand met from domestic production are lower. Completed vertical farms are less when the adjustment time is smaller as the loop *Decaying Vertical Farms* is strengthened, preventing the number of vertical farms from accumulating as much as when the adjustment time is higher. Meanwhile, demand met from domestic production is lower because as vertical farms decay more quickly with a lower adjustment time, this prevents capacity from increasing as quickly. This prevents demand for vertical farm produce from increasing as quickly and, thus, demand met from domestic production does not increase as quickly.

Desired self-sufficiency



This model is numerically sensitive to this variable. Desired self-sufficiency is the desire amount of demand that the government wants to meet from domestic production. This variable primarily impacts loop *Asking for Help (B10)*. By lowering the desired self-sufficiency, the government is lowering its self-sufficiency goal. With a lower goal, they more quickly meet the desired number of vertical farms and the desired amount of domestic production. In this model, this means that the government would then lower the number of subsidies going to vertical farm industry and shift subsidies towards other initiatives. This can be seen in completed vertical farms. As the amount of government funding to farms decrease, fewer farms can be constructed and the increase in completed vertical farms is slower. This leads to profits remaining higher. With fewer vertical farms producing, there are fewer overall expenses. Meanwhile, demand met from domestic production increases less quickly with a lower desired self-sufficiency because with a slower increase in the number of vertical farms, capacity increases less quickly which means demand for vertical farm produce increases less quickly.

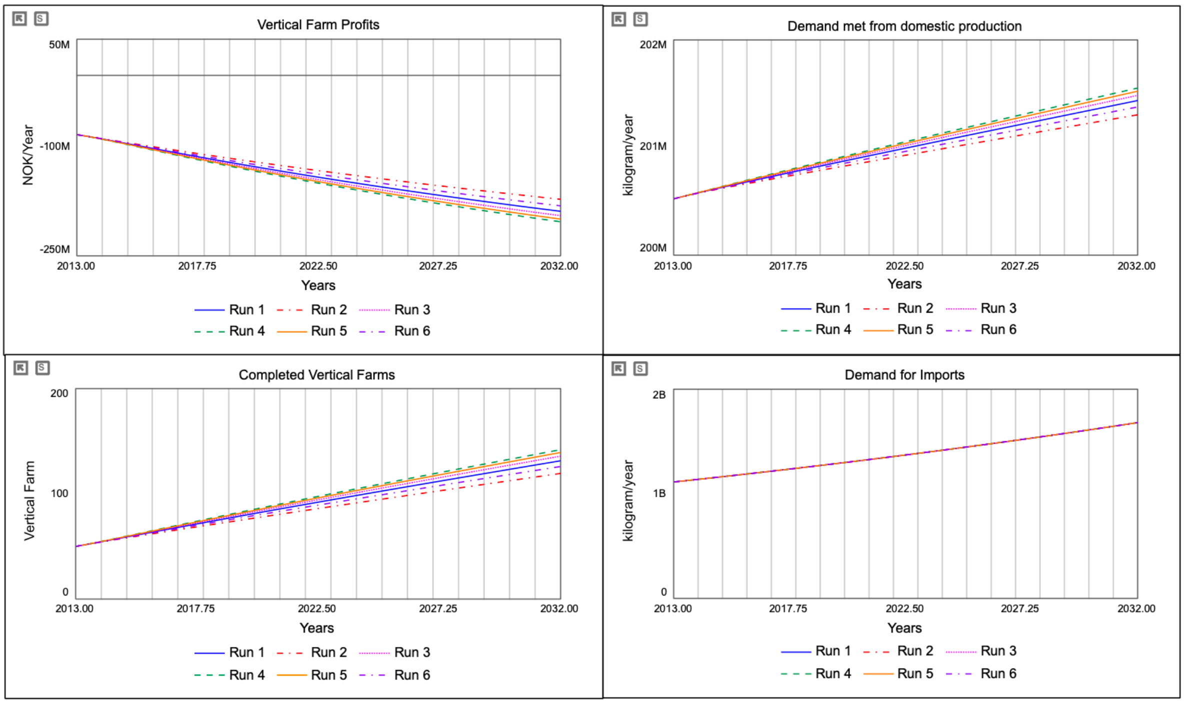
Inflection Point



The model is numerically sensitive to the inflection point. This variable indicates at what point the s-shaped effect of self-sufficiency gap on government subsidies shifts. With an inflection point less than 0.5, the self-sufficiency gap will have a larger influence on government subsidies. The government is willing to keep funding vertical farms even if the gap becomes smaller. Meanwhile, with a higher inflection point, this indicates that the government is willing to reduce the amount of funding more quickly towards vertical farms. This can be seen in completed vertical farms where the higher the inflection point, the lower the number of completed vertical farms. This is because *B10* is weakened and the amount of funds going to vertical farms diminishes. The opposite occurs when the inflection point is higher. The higher inflection point means that with fewer vertical farms, capacity increases less quickly, driving demand for vertical farm produce less quickly which means demand met from domestic production increases less quickly.

Profits remain higher with a higher inflection point as fewer completed vertical farms means less production occurs and fewer overall expenses as a result.

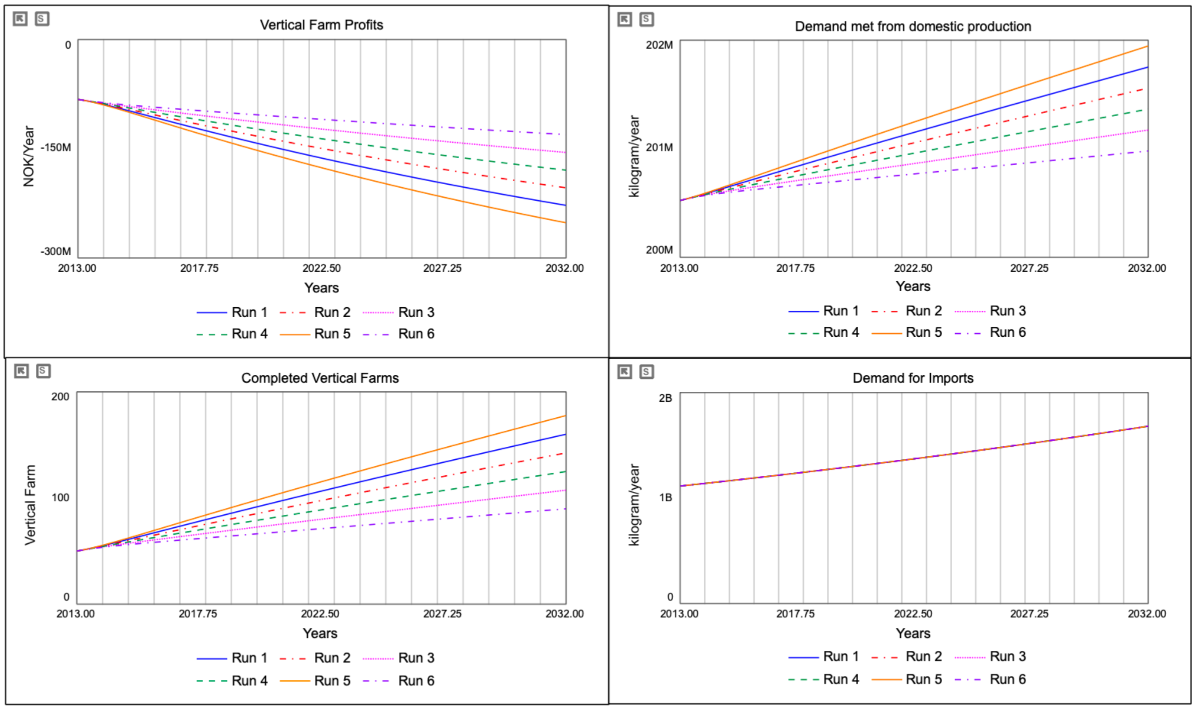
Steepness



The model is slightly numerically sensitive to steepness. Steepness indicates how quickly the s-shaped effect of self-sufficiency gap on government subsidies shifts. When the self-sufficiency gap increases, the government subsidies will increase towards the maximum subsidy value more quickly when steepness is higher. This can be seen in completed vertical farms. With a higher steepness, more vertical farms are completed as it requires less of an increase in self-sufficiency gap to trigger more subsidies to be given towards vertical farm construction. This means that with more farms, there is more capacity being met and thus more demand met from domestic production. Meanwhile, profits decrease due to the increased number of vertical farms and the corresponding expenses.

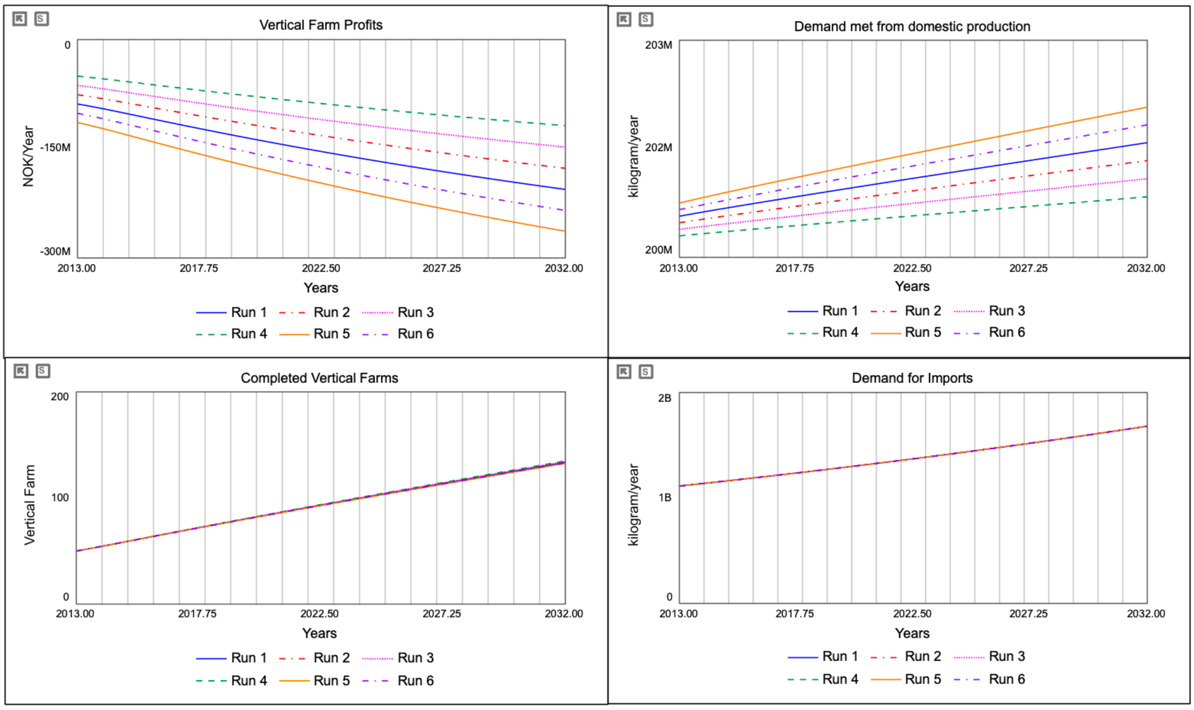
In contrast, a lower steepness shows that self-sufficiency gap must have a large increase to lead to more government subsidies to be given to vertical farming construction. As such, there are fewer completed vertical farms and a lower demand met from domestic production. Profits will remain higher as a result.

Indicated fraction of subsidies to vertical farms per year



The model is significantly numerically sensitive to the indicated fraction of subsidies to vertical farms per year. With a higher fraction, more of the allocated agricultural funds will be given to vertical farms. This leads to a higher number of completed vertical farms as well as a higher amount of demand met from domestic production and a lower profit. Meanwhile, a lower fraction, means less of the allocated agricultural funds will be given. Fewer farms can be completed as a result, meaning that capacity remains lower so that demand for vertical farm produce remains lower. As such, demand met from domestic production does not increase as quickly. Likewise, with fewer completed farms, profits are higher as there are fewer overall production expenses.

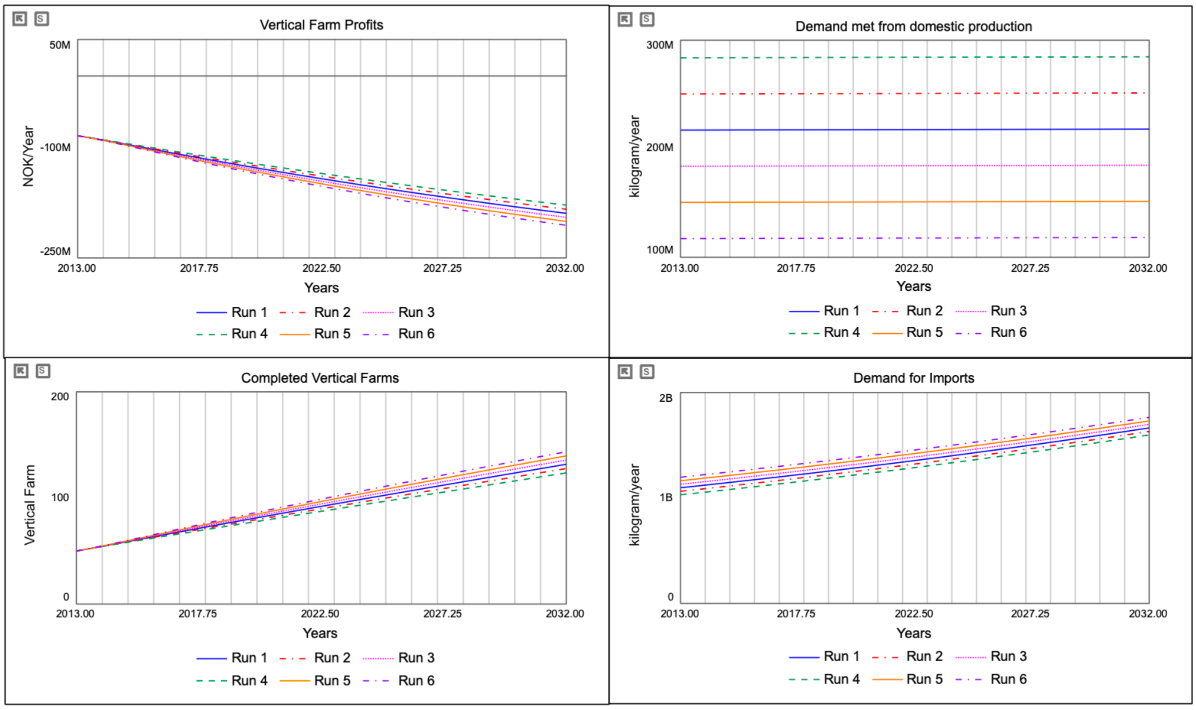
Average output per vertical farm



The model is numerically sensitive to the average output per vertical farm. This is most notable in the KPIs demand met from domestic produce and vertical farm profits. With a higher average output, vertical farms produce more per vertical farm. This also means that with a higher average output, the price per kilogram is lower as the average operational cost per kilogram is determined by taking the average operation cost per farm per year divided by the average output per vertical farm. With the price per kilogram decreasing, this drives demand from the *Price Comparison* loop. With a lower ratio between price per kilogram and price of imports, demand for vertical farm produce increases. This leads to more revenue and higher profits. However, since profits remain negative, completed vertical farms do not increase as much of this construction is led by government subsidies.

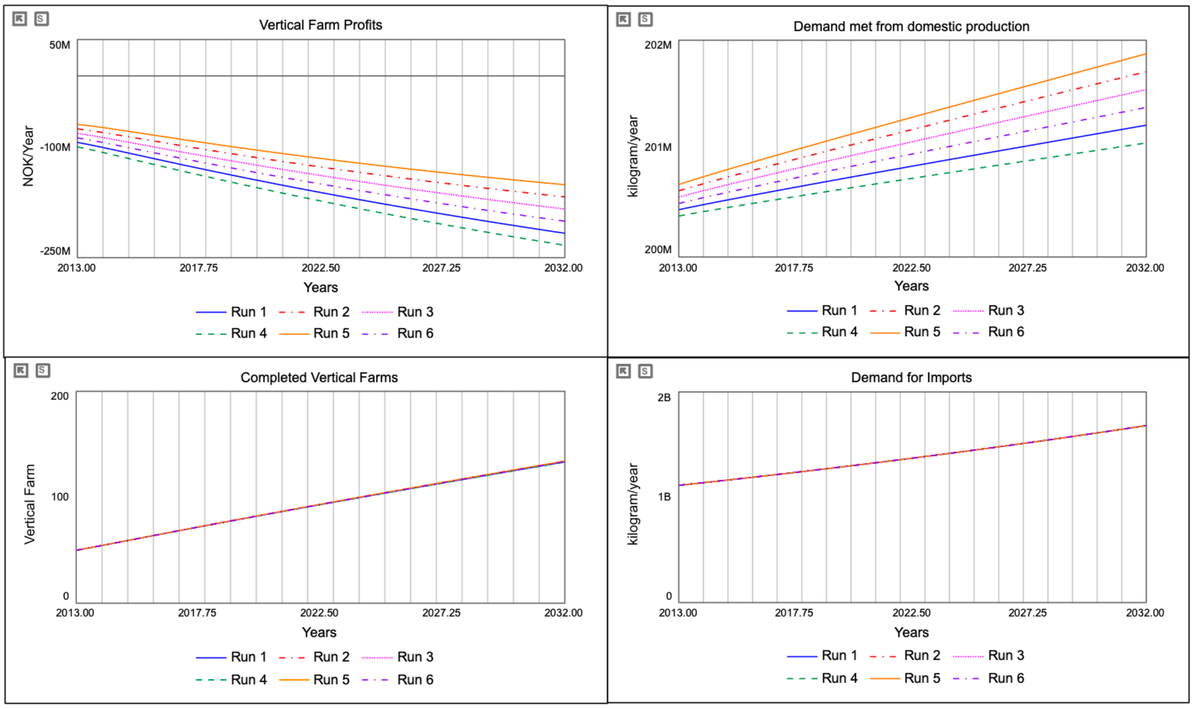
It should be noted that profits do not noticeably increase. In fact, with a higher average output, vertical farm profits decrease as it the more output leads to more vertical farm expenses as expenses are determined per kilogram of produce.

Demand fulfilled from conventional farms Norway



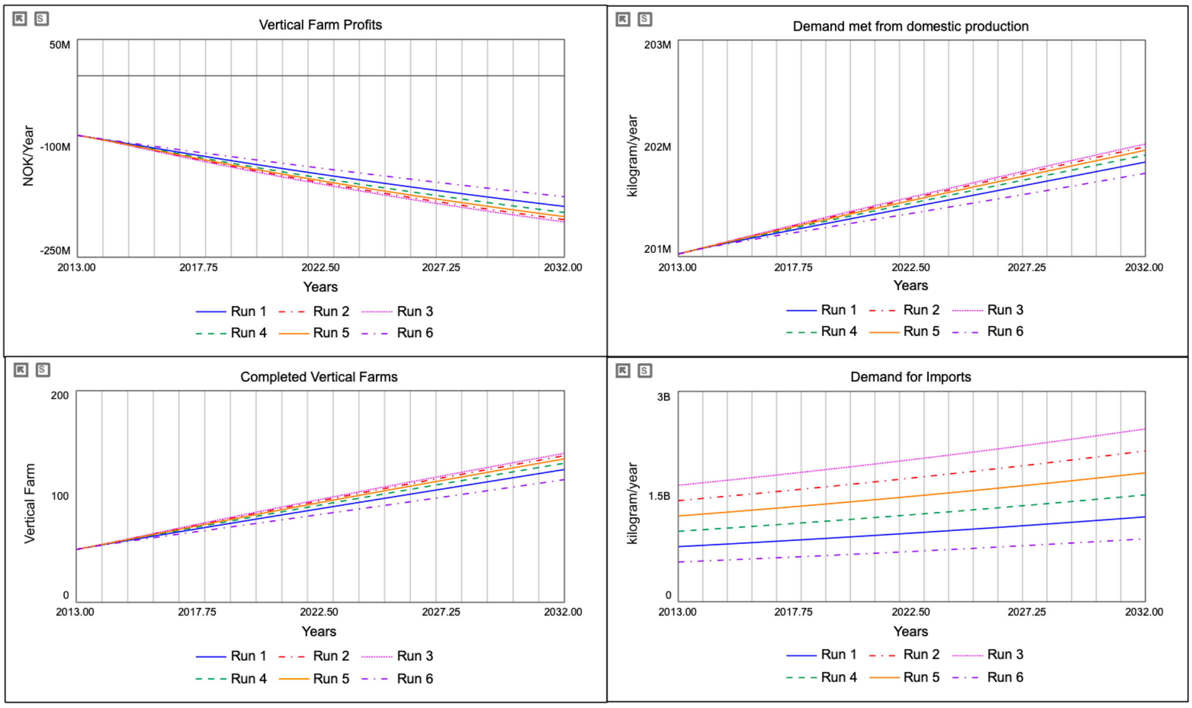
This is one variable that impacts all the KPIs to indicate numerical sensitivity. With a higher amount of demand fulfilled by conventional farms, the demand for imports decrease. This is simply because there is less unfulfilled demand that needs to be met, or covered, by either vertical farms or imports. Likewise, demand met from domestic production increases significantly. Meanwhile, there are fewer completed vertical farms with a higher demand fulfilled by conventional farms because there is now a higher achieved self-sufficiency. This lowers the self-sufficiency gap which lowers the amount of government subsidies available to vertical farms. The government sees that self-sufficiency is closer to its desired goal and will look to push funds to other initiatives. These funds drive vertical farm construction as profits remain negative. This means with fewer funds, there are fewer vertical farms being completed. This also means, that with fewer vertical farms being completed and, therefore, producing, expenses remain lower. Profits can be seen to be higher with a higher demand fulfilled by conventional farms.

Supply coverage



The model is numerically sensitive to supply coverage. Supply coverage impacts the amount of distributor orders which then impacts shipment to distributors. With a higher coverage, there will be a higher shipment to distributors. This means that more of the demand will be met from domestic production. There will also be higher revenues as a result. This increases profits. Since profits remain negative, vertical farm construction is still driven primarily from government subsidies and, thus, higher profits does not lead to significant changes in completed farms.

Reference per capita consumption



This model is sensitive to reference per capita consumption. It impacts all KPIs as well. With a lower reference per capita consumption, demand for imports is lower as this variable helps to drive the exogenous growth in total demand. However, with a lower total demand, this improves achieved self-sufficiency as there is less demand to be fulfilled. This means that there are less subsidies put towards vertical farm construction and higher profits as a result as fewer farms means less expenses. With fewer vertical farms, capacity remains lower and the demand for vertical farm produce does not increase as when there are more vertical farms. As such the demand met from domestic production is lower as a result as well.

Appendix D: Policy Analysis on Alternative Scenarios

With the base run policy analysis previously explained, I will first explain each scenario individually before providing analysis with the help of Stella's Loops that Matter tool.

Scenario 1: Supply chain issues in vertical farm construction.

In this scenario, I indicate that the construction of vertical farms is delayed by exogenous supply chain issues. Rather than taking one year to complete a farm, it will take five. This is deemed a likely scenario based on extended supply chain issues that have arisen globally across the world and that have persisted overtime. This scenario is implemented in year 2023. The run is shown in Figure E.1 below in comparison to the base run.

This scenario shows that when the delay in completing vertical farms is increased, it strengthens loop *B1,* limiting vertical farms from being completed. As seen, completed vertical farms stagnate but then increase with the same slope. Demand met from domestic production does likewise. Vertical farm profits stagnate but then declines along the same slope as the base run. This delay does little to change the behavior of the model other than delaying the process of completing vertical farms.

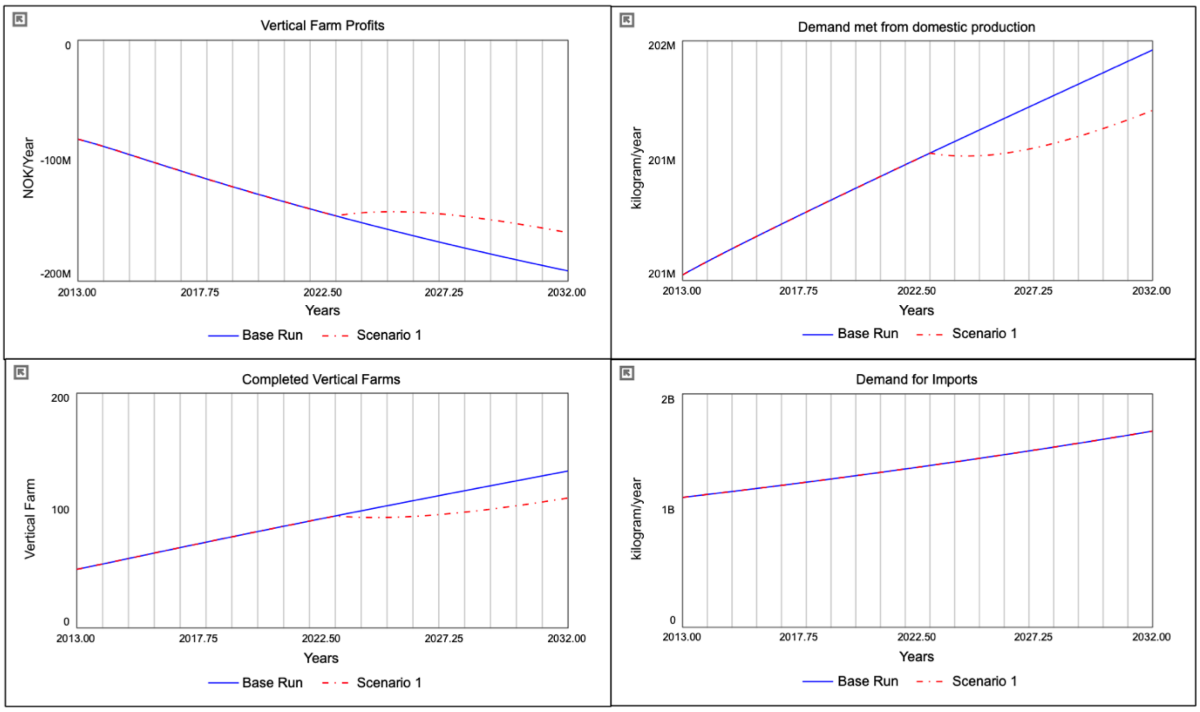


Figure E.1: Scenario 1

Scenario 2: Decreased subsidies from the government.

In this scenario, government subsidies will be lowered. A new political administration has come into power and the ruling majority in the Norwegian Parliament want to reduce the amount of funds allocated to vertical farming by two thirds the original fraction. This scenario is also implemented in year 2023. Figure E.2 showcases how this scenario impacts the model in relation to the base run.

As seen, this scenario immediately leads to completed vertical farms no longer increasing as there is a significantly smaller amount of funds made available to help construct vertical farms. Loop *Maturing Vertical Farms (B1)* increases in dominance to show a decline in the number of vertical farms. Farms are limited from being completed as fewer farms are being constructed initially. As a result, the profits increase as no new farms join production to increase expenses. Meanwhile, demand met from domestic produce declines as farm capacity is no longer increasing. This weakens demand for vertical farm produce and the demand met from domestic production. Demand for imports is not impacted as it is being driven by an exogenous population.

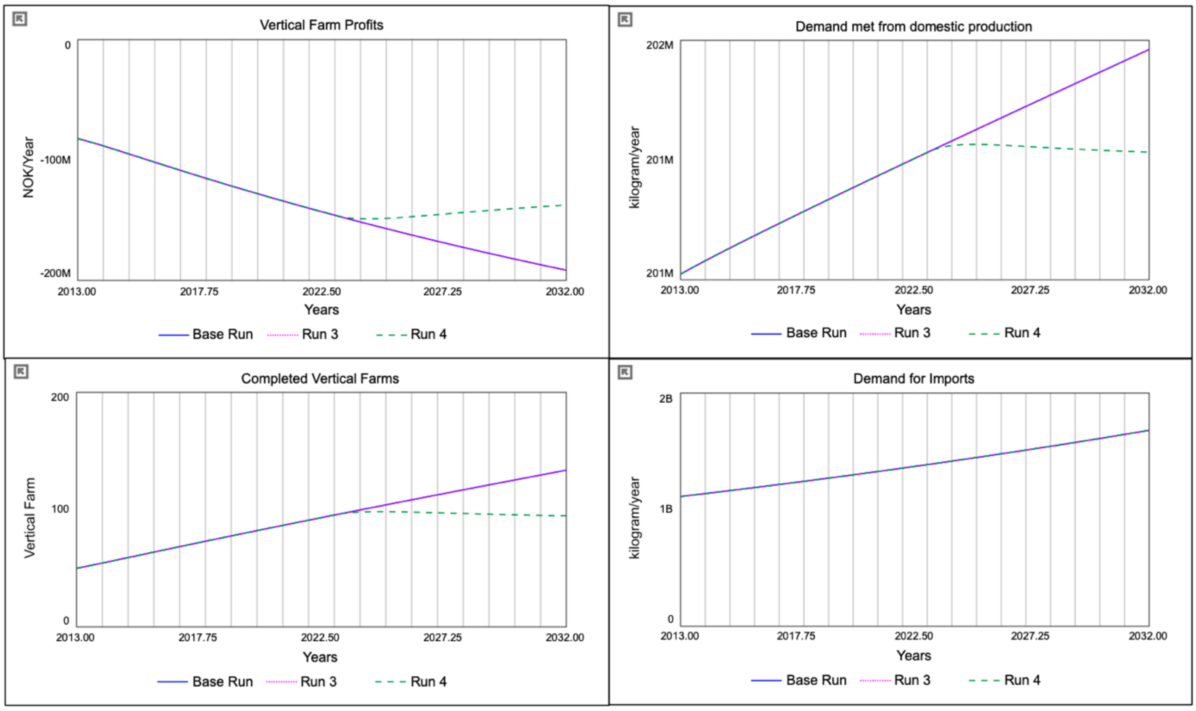


Figure E.2: Scenario 2

Policy Implementation on Scenario 1:

Looking towards policy implementation on Scenario 1 of supply chain issues, Figure E.3 shows four runs which include Scenario 1 without any policy implementation, Scenario 1 with Policy 1 enacted, Scenario 1 with Policy 2 enacted, and Scenario 1 with both policies enacted. The largest changes can be seen in vertical farm profits and demand met from domestic production.

Policy 2 on its own indicates that it has the weakest effect on the model. As it weakens loop *B2* by lessening energy needs with new LEDs*,* vertical farm profits increase albeit only to decrease at the same rate as the original Scenario 1 as it lessens the expenses coming from energy. There is also a small increase in the amount of demand met from domestic production as it helps to lower the price per kilogram which drives more demand for vertical farm produce, strengthening *Making the Money (R1)* loop. However, it does little on weakening loop *Maturing Vertical Farms (B1).* That loop remains dominant and limits the number of new vertical farms.

Meanwhile, Policy 1 shows a more significant impact. Much like the base run, Policy 1 increases the strength of *R1* by lowering the ratio between price per kilogram and price of imports. This drives demand for vertical farm production, which is seen in demand met from domestic production, and increases revenue, which is seen in a positive profit. However, it also has a limited impact on completed vertical farms. Loop *B1* remains dominant in its ability to limit vertical farm construction. Regardless of a large pool of funding available to construct vertical farms, a strong *B1* will limit the effectiveness.

Finally, with both policies enacted together, it shows the largest increase in profits and in demand met from domestic production. This occurs as loop *B2* is weakened and *R1* strengthened. Vertical farm profits will increase to its highest level and so too demand met from domestic production. Yet, completed vertical farms are not impacted. Even with both policies, *B1* shows its dominance in its ability to limit new construction.

Throughout each policy, demand for imports remain largely untouched. It shows that the exogenous driver for plant produce demand from population will not be impacted.

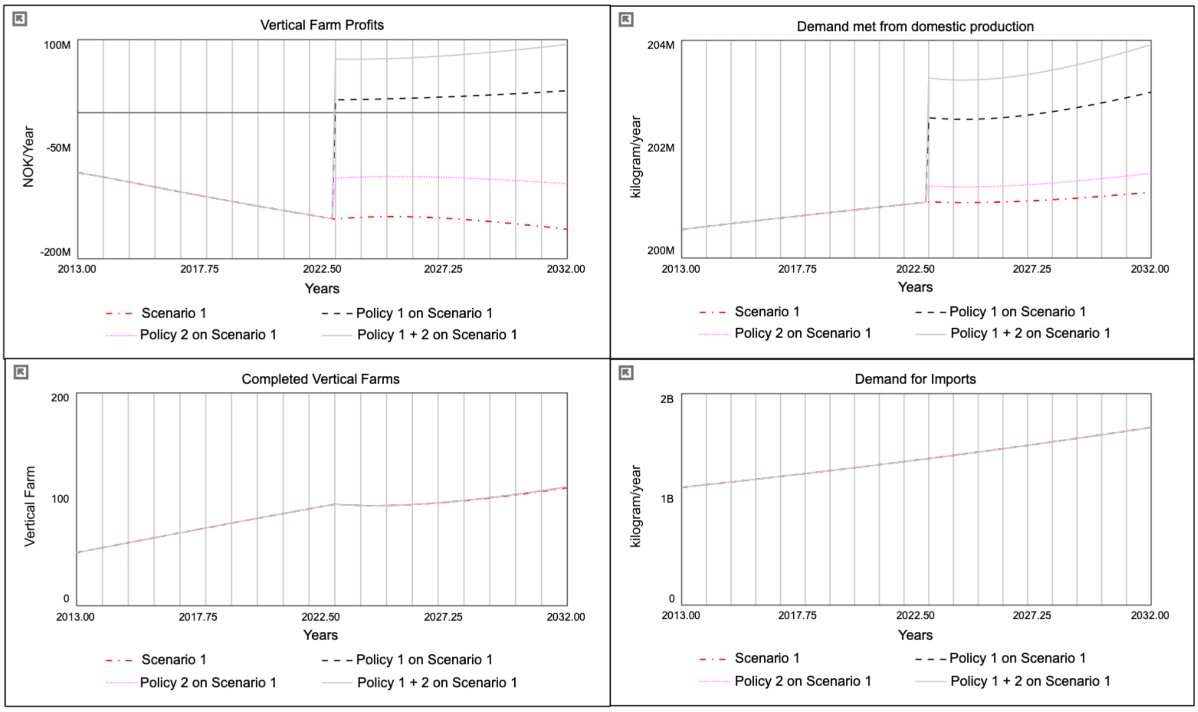


Figure 5: Policy Implementation on Scenario 1

Policy Implementation on Scenario 2:

Shifting towards policy implementation on Scenario 2 in which government subsidies towards vertical farming are reduced, Figure E.4 shows four runs which include Scenario 2 with no policies implemented, Scenario 2 with Policy 1 implemented, Scenario 2 with Policy 2 implemented, and Scenario 2 with both polices implemented. Again, the largest changes can be seen in vertical farm profits and demand met from domestic production.

When looking only at Policy 2 implementation, it has the smallest impact on the model. It weakens loop *B2* by lowering the energy need and expense in the model. It also drives revenue by strengthening indirectly loop *R1* by decreasing the price per kilogram in relation to price of imports which drives demand for vertical farm production. However, it is not enough to limit the strength of *B1*. Completed vertical farms begin a gradual decline as there are fewer funds to push further construction. As such, *B1* shows that fewer vertical farms are completed. However, it should be noted that demand met from domestic production increases but still declines similarly to Scenario 2 with no policy implementation. With no new vertical farms completed and *Decay of Vertical Farms (B3)* leading to a decay of farms, capacity declines which lowers demand for vertical farm production.

Policy 1 has a more significant impact in that it drives demand for vertical farm production by lowering the price per kilogram to price of imports ratio to below one. This then increases revenue enough so that profits become positive and increase gradually. This is strengthening *R1.* However, it is not enough to weaken the effect of *B1* as vertical farms are still limited from being constructed. This loop remains dominant as construction of vertical farms are largely driven by government subsidies. As such, completed vertical farms decline and demand met from domestic production stagnates and declines slightly because of a lower vertical farm capacity lowering demand. This counteracts the strengthening of *R1.*

Meanwhile, the policies enacted together show a stronger *R1* that is strengthened by both policies. Profits are at the highest level but increase gradually. Demand met from domestic production is increased significantly but declines as *B1* remains the dominant loop limiting new vertical farms from being built. Without new farms, capacity is lowered, lowering demand for vertical farm produce. This fully emphasizes that government subsidies play a critical role in the initial phases of vertical farm industry in Norway.

Finally, it should be noted that the demand for imports is again not impacted as they are being driven exogenously by population. Realistic policies to increase demand met from domestic production to then lower demand for imports is difficult to identify in the current version of this model.

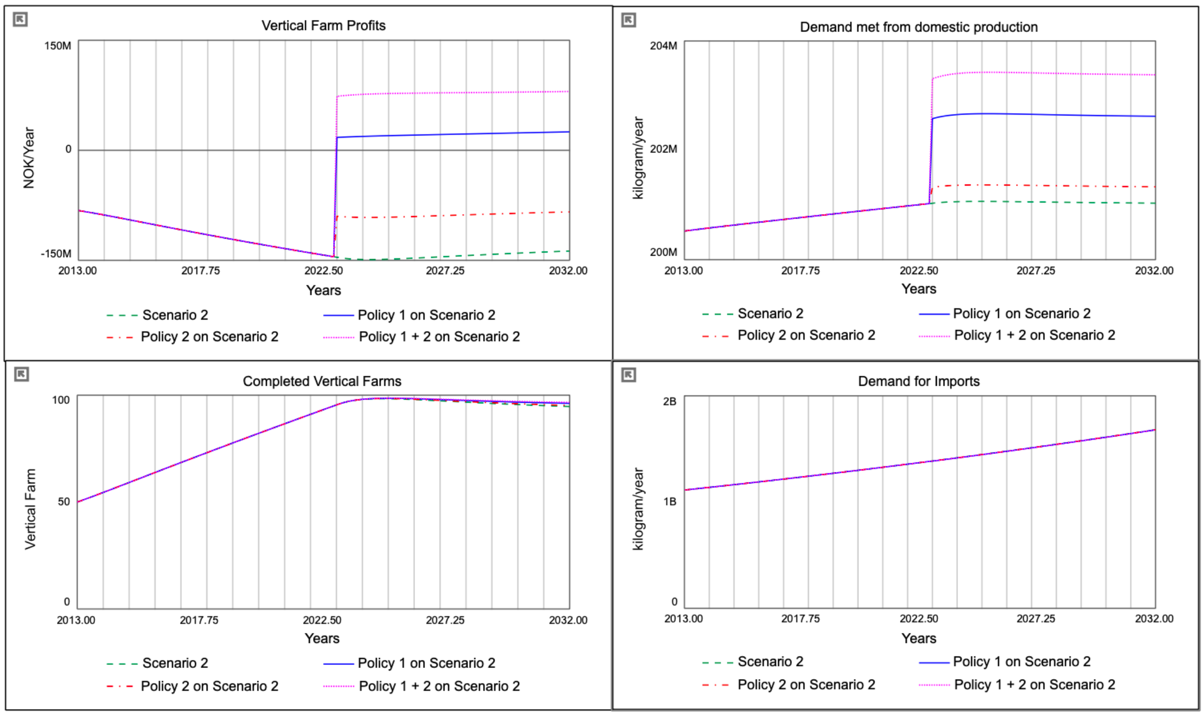


Figure E.4: Policy Implementation on Scenario 2

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