Supplementary Materials to

**Where Will Food Come From? A Look at the Potential of Vertical Farming in Norway**

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# Model Structure

## Vertical Farming Finances



Government Subsidies Sector

## Food Supply Sector

## Food Demand Sector

# 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 |
| 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. |
| 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. |
| 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\_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. |
| 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. |
| Completing\_Vertical\_Farms | Vertical\_Farms\_Under\_Construction/AVERAGE\_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. |
| Constructing\_Vertical\_Farms | (MAX(0, vertical\_farm\_income)/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. 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. |
| 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. |
| 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. |
| 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. |
| 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. |
| 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. |
| 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. |
| "achieved\_self-sufficiency" | (Shipment\_to\_Distributors+DEMAND\_FULFILLED\_FROM\_CONVENTIONAL\_FARMS\_NORWAY)//total\_demand | 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 demand fulfilled from conventional farms Norway which measures how much demand is met by existing conventional farms in Norway. |
| 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\_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. |
| 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\_PER\_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 | 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. |
| 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. |
| 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. |
| 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. |
| 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). |
| 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. |
| decay\_adjustment\_time | INDICATED\_DECAY\_ADJUSTMENT\_TIME\* effect\_of\_relative\_vertical\_farm\_income\_on\_decay\_adjustment\_time | Year | This is the decay adjustment time. It is determined by multiplying the indicated decay adjustment time and the effect of relative vertical farm income on decay adjustment time. |
| 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+Shipment\_to\_Distributors | 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. |
| "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. |
| 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. |
| 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\_relative\_vertical\_farm\_income\_on\_decay\_adjustment\_time | IF vertical\_farm\_income < 0 THEN MIN(MAX(MAX\_EFFECT, 1-SENSITIVITY\_OF\_EFFECT\_OF\_RELATIVE\_VERTICAL\_FARM\_INCOME\_ON\_DECAY\_ADJUSTMENT\_TIME\*(relative\_vertical\_farm\_income-1)), 1) ELSE 1 | 1 | This effect showcases how a change in the relative vertical farm income will impact the decay adjustment time. An IF, THEN; ELSE equation is included to indicate that this effect will only occur when vertical farm income is negative. When the industry is losing money, the decay adjustment time will decrease linearly to a maximum effect value. This indicates that the vertical farm industry will collapse more quickly the larger the relative vertical farm income is up until the maximum effect value. However, a MIN function is also included to indicate that this effect impacts the decay adjustment time between the maximum effect and 100% of the decay adjustment time value. |
| "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. |
| effect\_of\_vertical\_farm\_ratio\_to\_cost\_reduction\_change\_rate | ratio\_of\_vertical\_farm\_to\_initial\_vertical\_farm^SENSITIVITY\_OF\_RATIO\_OF\_RELATIVE\_VERTICAL\_FARMS\_ON\_COST\_REDUCTION\_CHANGE\_RATE | 1 | This effect shows how the increase in the ratio 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. |
| 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\_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\_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 |
| FRACTION\_OF\_NET\_REVENUE\_REINVESTED | .8 | 1 | This is an assumed value that determines the amount of vertical farm income that is reinvested back into vertical farming. Since the goal is to establish more vertical farms, it is assumed that the majority of net revenue will be reinvested, but not all as it is the goal of the firm to save some of that money. |
| fraction\_of\_subsides\_to\_vertical\_farms\_per\_year | 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. |
| FRACTION\_OF\_SUBSIDIES\_TO\_VERTICAL\_FARMS\_PER\_YEAR | INDICATED\_FRACTION\_OF\_SUBSIDIES\_TO\_VERTICAL\_FARMS\_PER\_YEAR\*(1-SCENARIO\_SWITCH\_2) + (INDICATED\_FRACTION\_OF\_SUBSIDIES\_TO\_VERTICAL\_FARMS\_PER\_YEAR-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. |
| 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). |
| gross\_revenue | Shipment\_to\_Distributors\*price\_per\_kilogram | NOK/Year | Gross 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. |
| 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. |
| INCOME\_LOSS\_THRESHOLD | -3e6 | NOK/Year | The income loss threshold indicates a a value in which the vertical farm industry would no longer function. If the industry has more losses than the given value, it would begin to decay much more quickly. This value is assumed based on research. The Norwegian government provided businesses who lost revenue during the COVID-19 pandemic 60000 NOK per year (FAS, 2020). This value was then multiplied by the initial completed number of vertical farms which is 3000000 NOK per year. It is assumed that if the vertical farm industry had a loss of more than 3000000 NOK per year, there would be no viable means of sustaining the industry. Below this value, there is infrastructure that exists to get emergency funding to sustain the industry. |
| 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\_DECAY\_ADJUSTMENT\_TIME | 30 | Year | The indicated decay adjustment time is an assumed time that vertical farms last when the industry is profitable. 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. |
| INDICATED\_FRACTION\_OF\_SUBSIDIES\_TO\_VERTICAL\_FARMS\_PER\_YEAR | 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\_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). |
| 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. |
| 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\_POPULATION | 5051275 | person | This is the initial population in the year 2013. This data was found from Statistics Norway database (2022). |
| 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. |
| LOWERED\_FRACTION | STEP(.3, 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. |
| 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. |
| MAX\_EFFECT | MINIMUM\_DECAY\_AT/INDICATED\_DECAY\_ADJUSTMENT\_TIME | 1 | This variable is the maximum effect of the relative vertical farm income when the industry is not profitable. It is determined by the indicated decay adjustment time divided by the minimum decay adjustment time. |
| MINIMUM\_DECAY\_AT | 1 | year | This is the minimum decay adjustment time. This would be the minimum decay rate at which vertical farms run out of business when the industry is not profitable. |
| NET\_MIGRATION\_FRACTION | 0.008 | 1/year | Net Migration data was found in Statistics Norway (2022). The data used from this source takes the Net Migration in 2013 divided by the Population in 2013.This value is the Net Migration Fraction found in 2013 which is used for this model. |
| net\_revenue | gross\_revenue-(labor\_cost+energy\_cost+water\_cost+operational\_cost) | NOK/Year | Net revenue showcases the amount of money generated from vertical farm production. This is determined by the gross revenue generated subtracted by the sum costs. |
| 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. |
| 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. |
| 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). |
| 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(Completed\_Vertical\_Farms) | 1 | This converter is the ratio of vertical farm to initial vertical farm. This is meant to represent how much the vertical farm 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. |
| 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. |
| relative\_vertical\_farm\_income | vertical\_farm\_income//INCOME\_LOSS\_THRESHOLD | 1 | This variable indicates relative vertical farm income. It is determined by taking the vertical farm income divided by the income loss threshold. This variable showcases that if vertical farm income were to fall below zero, the larger the negative value would lead to a larger relative vertical farm income. |
| remaining\_demand\_to\_be\_fulfilled | MAX(total\_demand-DEMAND\_FULFILLED\_FROM\_CONVENTIONAL\_FARMS\_NORWAY, 0) | 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 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. |
| 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. |
| 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\_EFFECT\_OF\_RELATIVE\_VERTICAL\_FARM\_INCOME\_ON\_DECAY\_ADJUSTMENT\_TIME | 1 | 1 | This parameter determines the sensitivity of the effect of relative vertical farm income on decay adjustment time. It was determined as there is uncertainty about the appropriate sensitivity and it was assumed that relative vertical farm income would impact decay adjustment time linearly. |
| SENSITIVITY\_OF\_RATIO\_OF\_RELATIVE\_VERTICAL\_FARMS\_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. |
| 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. |
| 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. |
| 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. |
| 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. |
| 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. |
| 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\_income | IF net\_revenue > 0 THEN (net\_revenue\*FRACTION\_OF\_NET\_REVENUE\_REINVESTED+government\_subsidies) ELSE (net\_revenue+government\_subsidies) | NOK/Year | The vertical farm income is the total pool of money made available to be reinvested in vertical farming. This is determined by the addition of net revenue and by government subsidies. An IF, THEN, ELSE function is used to showcase that if net revenue is positive a fraction of the revenue will be taken by the industry with the rest being put back into building more farms. However, if there is no net revenue, then there is no revenue to be taken. |
| 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. |
| 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. |

# Sensivity Analysis

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Description automatically generated with medium confidenceFor 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.

## Average Price of Imports

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Looking first at average price of imports, this variable shows numerical sensitivity and I use this in my policy analysis as a leverage point. There is sensitivity 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, increasing vertical farm income as well, driving down the price per kilogram through the economies of scale and further reducing the ratio. 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, 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

A collage of graphs showing different numbers

Description automatically generated with medium confidence

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, vertical farm income is higher 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

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I 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.

## Profit Margin

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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

A collage of graphs

Description automatically generated

This model is numerically sensitive to this variable. The KPIs vertical farm income 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. Yet, with income increasing very little, this shows that vertical farms are being built more so from government subsidies. Since the completed number of vertical farms do not change, it indicates that the subsidies loops are not impacted. Still, further farm construction leads to reduced prices due to economies of scale which further reduces the price driving demand for vertical farm produce.

## Average Energy Need

A collage of graphs

Description automatically generated

This model is numerically to average energy need. This is seen most notably in vertical farm income and demand met from vertical farm production. As energy need is reduced, the higher the income 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

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Description automatically generated

Much like energy need, this variable showcases numerical sensitivity through the KPIs of vertical farm income and demand met from domestic production. As the cost per kw is lowered, the income 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. 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

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Description automatically generated

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. 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 vertical farm income from increasing significantly.

## Initial Vertical Farms Under Construction

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Description automatically generated

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. 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.

## Initial Completed Vertical Farms

A collage of graphs showing different numbers

Description automatically generated with medium confidence

The model is numerically sensitive to initial completed vertical farms. This can be seen in the KPIs of demand met from domestic production and completed vertical farms. With more farms, the industry produces more but, in doing so, increase the expenses. Demand for vertical farm produce will increase as vertical farm capacity is increased with more vertical farms. As such, we see numerical change, but not a change in behavior.

## Indicated Decay Adjustment Time

A collage of graphs

Description automatically generated

The model is numerically sensitive to indicated decay adjustment time. This variable indicates how quickly completed vertical farms decay and go into disuse. 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 (B3)* 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. Vertical farm income is being driven by government subsides which results in less sensitivity.

## Desired Self-Sufficiency

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Description automatically generated

This model is behaviorally 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, vertical farm income decreases, and the increase in completed vertical farms is slower or, at a certain point, completed vertical farms begin to decline. 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 if not begin a decline.

## Inflection Point

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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 increasing vertical farm income and fund new 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.

## Steepness

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Description automatically generated with medium confidence

The model is 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 and vertical farm income. 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.

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, less vertical farm income, and a lower demand met from domestic production.

## Indicated Fraction of Subsidies to Vertical Farms per Year

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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 amount of vertical farm income and completed vertical farms as well as a higher amount of demand met from domestic production. 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, vertical farm income will be lower.

## Average Output per Vertical Farm

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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 income. 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 (R5)* 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 vertical farm income. However, the increase in income is not significant enough to lead to more farms. The increase in farms is still largely driven by subsidies.

## 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 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. This means less vertical farm income and, thus, there are fewer vertical farms being completed.

## 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 also increases vertical farm income but not enough to make significant changes in completed vertical farms. This indicates that income is driven largely by subsidies.

## Reference per Capita Consumption

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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 due to less vertical farm income. 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.

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