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Food Security by Vertical Farming

Anusha Naik

Table of Contents

ABSTRACT

While our civilization wouldn't be where it is today without agriculture it's a big factor in a number of humanity's greatest challenges If we continue as we are we will likely have to cut down more of our remaining forests for land destroying even more land and freshwater habitats in the process. We will permanently degrade more fertile land into deserts while significantly increasing our greenhouse gas emissions. Instead of reducing them. Perhaps the highest risk of all for Humanity is water scarcity. Current projections make a global water crisis almost certain. In light of these challenges, we probably want to ask if there is a way to reduce the negative impact of current agricultural methods. It's worth remembering that this data is the global picture. If all of agriculture used the best practices and technologies.

Introduction

The world is facing some major problems food security, water security species loss climate change. Vertical farms have been proposed as part of the solution to these global problems But is it just another overhyped technology, with great claims but lacking in practical application? This research paper is going to cover vertical farming in context of current agricultural techniques and Investigate whether this technology can really help solve them. But first what is a vertical farm vertical farm is essentially an indoor farm that uses soilless technology (hydroponic or aeroponic) to grow food
Rather than being restricted to two dimensions. They stack levels on top of each other and make use of artificial lighting The combination of highly controllable growing conditions, optimal light levels at all times full year-round growing and harvesting give vertical farms an incredible yearly output, for a given area of land and it doesn't really matter where in the world you place them, in the desert, in the city in Antarctica, even on Mars But while you could technically place them more or less anywhere, should you? Why waste energy lighting plants artificially? When the Sun does it naturally? Why build towering racks, when the world is covered in fertile land? To understand why we might want to First we must have a quick look but the tremendous success of agriculture and its impact on the world
simply put agriculture is one of humans oldest and most important innovations
a practice over 12,000 years old yet, it continues to deliver Using the USA as an example, in 1790, 90% of the population were farmers. Today that number is just 1% Yet despite this staggering reduction in farmers, the USA can still feed its citizens.

In fact, it's the world's largest exporter of food! This amazing feat, is due to magnitudes of improvement in efficiency. And that efficiency is crucial, because the world as we know it, wouldn't be here without it. Today, the global population stands at 7.6 billion. Over 4 times higher than it was 100 years ago, yet this recent population boom would have been impossible without an associated boom in agricultural productivity But scaling up agriculture is not without some serious side effects

And it's contributing to some major global issues So let's take a look at some

GLOBAL CHALLENGE: FOOD SECURITY

The UN predicts world population to reach 9.8 billion by 2050 With an increasing demand for food in the developing world and an increased demand for meat in particular According to the FAO, we will need a 70% increase in our global food production by 2050 If we take technological improvements into consideration, will we have enough land to meet this increase? Global food yields increase every year on average. With the projected non confounding yearly growth rate, of 0.65% percent Yet despite yield improvements The demand will still lead to an expected 12% increase in cropland. An area of 2 million square kilometers unfortunately, it's not the only increase. A profitable market for biofuels exists and is expected to increase by 2050 The global biomaterials market is also expected to grow significantly Taken together these will increase the cropland required by an additional 1.2 million square kilometers Taking our 2050 cropland increase up to 21% This is an area around the size of India. The bad news isn't over though. We are also losing our existing land Farmable land is set to be turned into an urban environment With the global urban footprint expanding by 33% meanwhile, desertification turns previously farmable land sterile Combining these effects, the loss of land relative to the current cropland, is 18%. That's a considerable amount of land Do we even have enough farmable land left ?

As of 2005 the world was 71% ocean and 29% land 66% of that land is considered farmable. of that, ,we see that 51% is already being used for agriculture, with 40% being forests and 6% shrubland ,If we factor in our 2050 model and take cropland increases and land losses into account, we get the following We still have enough land left to feed the world of 2050 But we essentially have no spare farmable land left globally This model doesn't even account for the anticipated yield loss Related to climate change, nor any additional grazing land for the projected 73% increase of meat consumption ,These factors, make the likelihood of cutting down significantly more global forests in 2050 almost inevitable global deforestation last year was a hundred and 180,000 square kilometres. ,An area around the size of England Vertical farming may not be needed to ensure we can put food on the table We do have enough capacity in hand to prevent mass starvation But the land requirements to keep the global population sustained, points us to our next global challenge But first, a quick note on global hunger Even though we produce enough food today to feed all 7.6 billion people on earth ,870 million people suffer chronic undernourishment due to a lack of food. That's eleven percent of the population! However, global hunger is more than just a food production problem.

DEFORESTATION

The increasing demand for land comes at a steep environmental price,since humans first wielded axes We've cut down over half the world's forests and it's not been without consequence in fact, some scientists argue that the world is undergoing its sixth mass extinction event as evidence by massive animal population reductions According to the

World Wildlife Foundation We've lost 38% of land animals in the last 40 years primarily from habitat destruction,It's not hard to see why,This 50% has only appeared in the las t 12,000 years,with most of it happening in the last hundred years or so.,That 50% used to be forests or shrub land,However, it's not just deforestation,freshwater animal populations have seen an alarming,81% reduction,since 1970,Agriculture is the main contributor to this,primarily draining wetlands to create cropland,In fact, 50% of the world's wetlands have disappeared since 1910,water consumption for irrigation further depletes local water levels, damaging habitats,agricultural runoff such as pesticides,Finds its way into local water systems poisoning wildlife. Runoff fertilizer can cause massive algae blooms,Draining the water of oxygen and creating dead zones.

Desertification

Desertification is a process where fertile land turns into desert, unable to support crops,and it's happening at a significant rate?,Greater than 3 times the area of Switzerland, every single year, Agriculture is the primary reason, with over grazing, overdrafting of ground water. Deforestation and tillage practices all contributing to the problem. In China it's happening at a huge rate,with 2,000 square kilometers per year,Turning into desert and about 10 times that area becoming significantly degraded,These are creating large dust storms that are making Beijing's already bad air pollution even worse,Beijing is now less than 70 kilometers from the rapidly encroaching desert and,Projected to be encircled by it in less than 20 years,This is a big problem for China,40 years ago,China was a net exporter of food yet. Now, it's the world's biggest importer of food by far.

CLIMATE CHANGE

All of the countries in the world with the exception of the United States have agreed to the Paris climate Accords,The aim is to limit the global average temperature rise to 1.5 degrees,Celsius this century, against a baseline of pre-industrial levels. Preventing the temperature rise,essentially focuses on reducing emissions of greenhouse gases,This is going to be a huge challenge because much of civilization as we know it is built around,technologies that cause greenhouse gas emissions in some form,Climate change is a topic that will crop up in a number of my future videos. But for now we will focus on Agriculture's role,Agriculture is a big player in the emission game, while the conversation is usually around carbon dioxide,Agriculture's primary responsibility is related to far more potent greenhouse gases: methane and nitrous oxide,Methane is mainly produced by beef production, while nitrous oxide is produced,primarily through fertilizers,converting methane and nitrous oxide into a carbon dioxide equivalents and also taking into account that agriculture is,responsible for 75% of global Deforestation,we see that agriculture is responsible for 18.3% of global emissions,And that is excluding its transport footprint. With an increasing demand for food,,land and a diet shift towards more meat,Agriculture can be expected to contribute close to double its already large footprint,This is a great concern at a time when the Paris Accords target aggressive emission reduction.

WATER SECURITY

On Planet whose surface is 71% ocean. It seems surprising to hear that we are running out of water,But we are,According to NASA the majority of the world's fresh water supplies are draining faster than they are being replenished,Agriculture is responsible for,92 percent of the global freshwater usage and since agricultural demand is set to nearly double,Fresh water demand is set to increase by 55 percent,By 2050. This represents a major problem even for developed countries with places such as Western, Australia,California the Gulf states China for developed countries,this may be manageable, because they can afford water imports and even desalination. But for North Africa the,situation is particularly critical. If more countries are forced to import water then prices increase,This can make water prohibitively expensive for many developing nations that find themselves short on water.

VERICAL FARMING: FUTURE OR FANATSY?

vertical farming has been called the future of Agriculture claimed to solve ,many of the problems we talked about in the last video. It's been a controversial ,topic with mixed opinions from experts. Are these claims hype or can it deliver? ,but first we need a better understanding of what a vertical farm is ,There are many different versions and they all have vastly different capabilities. ,Part of the problem, is the many types of farm and confusing array of definitions ,So let's deal with those first. ,vertical farming and urban farming are both umbrella terms that are sometimes ,used interchangeably, although they are not the same. Urban agriculture includes ,a broad array of concepts, it essentially focuses on bringing food production into ,the city. In order to move the production as close to consumption as possible. ,This may include the usage of vertical farms or may involve more traditional growing ,practices, in an urban environment. While vertical farms can be urban, they don't ,have to be, therefor all vertical farming references in this research paper won't ,be restricted to urban environments.

HYDRO, AERO, AQUA

While vertical farms can use soil most ,utilize hydro, aero, or aquaponics. These methods use much less water than ,typically used in soil. Hydroponics replaces soil by using a circulating ,water and nutrient mix for plant growth. Aeroponics uses an open membrane and a ,water mist spray with a nutrient mix. Aquaponics uses hydroponics and an ,aquatic ecosystem to balance nutrients in both systems. ,Strictly speaking, the term vertical farm ,could be used in reference to structures that grow food on multiple levels. This ,could range from small-scale hobby spaces, to large automated buildings. So ,let's quickly take a look at which versions of this technology, have the ,most promise to positively impact our global issues.

SKYSCRAPER FARMS

For many, the image of the ,vertical farm is a city skyscraper filled with fruit vegetables trees and ,perhaps even animals. Whilst some look amazing, it can be hard to argue that ,these images lend credibility to the vertical farming concept. Skyscrapers ,represent very expensive real estate and are usually reserved for high-value ,activities. Growing fruit on trees or rearing animals humanely, have a low ,value density. This isn't a problem if you have ,acres of cheap land to produce on, but it is if you're using premium real estate. ,Even if you're growing a dense premium crop, the cost of growing also increases ,exponentially with height. The requirements to pump water and move ,biomass vertically, takes considerable energy. This may be insignificant for a ten ,level farm, but would likely be prohibitive for a farm with hundreds or ,thousands of levels. While there are a number of architectural concepts for ,skyscraper farms, as yet, only one is being built. The world food building is ,currently under construction in linköping Sweden. While information for ,this building is limited, even if it achieves its target costs of 40 million ,dollars, It is highly unlikely to recoup that money with its production capacity ,of 550 tons of vegetables per year. Wall farms and rooftop farms often share a ,similar visual appeal to skyscraper farms. Unlike skyscraper farms, these ,don't displace existing real estate. Instead, they aim to utilize unused ,spaces to grow food. As such, the cost of adding these types of farm is often ,minimal. Many of these farms are created by hobbyists and double as Gardens. As ,such, the addition of green space to the urban environment is considered a ,welcome one. While this may seem like good news, the amount ,of usable surfaces for growing food, is extremely limited. In fact, Dickenson Despommier, the man who is credited with inventing the term vertical farm came up ,with the concept, after his students calculated that rooftop farming could ,supply just 2% of 2015 New York's population, by fully utilizing all of its ,rooftops for growing. This is when he turned to the idea of skyscraper farms. ,Even if we utilize all usable rooftops in the world, we would only be able to ,save a fraction of a percent the global land. so while rooftop and wall ,farms aren't a bad use of otherwise wasted space, their ability to affect the ,global challenges are negligible.

VERTICAL GREENHOUSES

Vertical greenhouses are largely transparent structures, that utilize ,multiple growing levels. One of the challenges that is introduced by ,stacking greenhouse levels on top of each other, is providing enough light as ,the glass or polymer structure already absorbs some of the sunlight and ,stacking vertically increases the risk of shadows. Vertical greenhouses can get ,around this problem by rotating the levels, to get a relatively even ,distribution of sunlight. By adding supplementary artificial light, vertical ,greenhouses can grow to higher plant density than a ,typical greenhouse. Although capital costs and electricity ,costs are higher. This makes them better suited to urban environments, where land ,is at a premium. Vertical greenhouses essentially allow you to move production ,closer to consumption. Both horizontal or vertical hydroponic greenhouses are ,promising technologies, that will help comeback the global challenges, as they ,require 10 to 15 times less land and water than traditional agriculture. Given ,that commercial hydroponic greenhouses are a relatively mature industry, their ,viability and scalability is not in question. These greenhouses can grow a ,broad range of fruits and vegetables but are not used to grow staple crops such ,as wheat, which accounts for the majority of land and water demand. They're also ,partially exposed to the climate and local light levels, which makes them ,expensive to run in some areas. If we use greenhouses to produce our global ,vegetables and some fruits, we would save less than 2% of our global land, barely ,enough to offset a projected 2050 land loss and less than half of the 55% ,increase in water demand. While greenhouses may alleviate some of the ,global challenges, it's not enough to be able to prevent the worst of the ,problems. If we really want to stop and reverse the global challenges, we will ,need a more radical approach.

PLANT FACTORIES

Plant factories are the most technologically ,advanced version of the vertical farm. They are airtight, highly ,climate-controlled buildings, with a co2 enriched atmosphere. They're essentially ,clean rooms, like those used in drug or satellite production. Production rooms ,contain plants on multiple levels, they are sealed and thermally insulated with ,no windows. Relying on 100% artificial lighting. they're aero, or hydroponic, where ,transpired water vapor from the plant is captured and condensed recycling it back ,into the hydroponic nutrient mix. They are typically warehouse size buildings, no ,more than a few stories in height. Plant factories offer the greatest level of ,land and water savings of all vertical farms. They also have the highest level ,of control and growing conditions, meaning that they can grow any type of ,plant, in any region of the world. They're not exposed to bad weather or failed ,harvests, this gives them the potential to have the greatest impact on the ,global challenges. ,plant factories, are the most viable ,version of this technology, although as we will discover, plant factories ,introduce their own challenges. While they have a greater level of real-world ,practicality, they still face criticisms around cost, real estate and energy ,consumption. So how valid are these criticisms?

IS VERTICAL FARMING VIABLE?

In order for vertical farming ,to positively change the world, it needs to be technologically feasible, ,environmentally sustainable (or at least better than current practices) and ,economically viable. ,While this industry is still in an early phase, from a technological standpoint ,vertical farming works. While it is true that the current farms focus almost ,exclusively on leafy greens and herbs, pretty much any crop can already be ,produced this way, with existing technology. Vertical farms use less water ,than traditional agriculture, a lot less. In the best vertical farms, one kilogram ,of lettuce requires 1.2 liters of water. This is especially impressive given that ,lettuce is 95% water. 1.2 liters is 17 times better than a normal hydroponic ,greenhouse and in stark contrast, field grown lettuce requires a staggering 237 ,liters per kilogram of lettuce. That's 200 times more water! The water saved has ,the potential for a huge positive impact on water security and reversing wetland ,destruction. Vertical farms don't need pesticides, they require little ,fertilizer and don't have uncontrolled agricultural runoff. These factors ,combined is great news for freshwater wildlife. Since they can be built near ,population centers, proponents of this technology often argue that urban farms ,allow for a reduction in carbon emissions, due to a reduction in food ,transport. While this is largely true, the extent of the benefit is often ,exaggerated from a climate perspective. Food transport makes up a relatively ,small portion of agricultural emissions, the real environmental opportunity for ,vertical farming, is the potential to return farmland to forest and shrub land. ,This will be a massive benefit for wildlife conservation efforts and also ,has promise for significant global carbon sequestration. But how much land ,can it save? This technology has a vastly greater yield for a given area, with the ,cutting edge farms having a growing density over ,100 times greater than field grown. This has enormous potential for ,reversing deforestation and habitat destruction. There is an elephant in the ,room however, vertical farms trade energy for density control, it's how they achieve ,massive yields for a small area of land. Artificial lighting accounts for 80 ,percent of the farms energy costs, based on the current global energy mix, most of ,that energy requires carbon emissions to produce. So on balance, are plant ,factories good for the environment and can they be solar-powered?

ECONOMIC

Vertical farms can be ,expensive to set up, especially if you want a big operation. Running costs can ,be high from a labor and electricity perspective. While labor costs decrease with ,the scale of the operation, it is difficult to shrink the electricity costs. Plants ,need light energy to grow, in a field the sun provides it for free, in a vertical ,farm, it must be supplied. Since leafy greens and herbs have a low ,light requirement and reasonable profit margins, they are much more economically ,viable. There are hundreds of them in operation around the world, some of them ,are massive in scale. Capable of producing 30,000 heads of lettuce ,per day from a single farm. A 2014 study of 165 Japanese vertical farms found ,that 25 percent were profitable, 50 percent were breaking even and 25 ,percent were making a loss. These are promising numbers for such a ,new industry. Rapid technological improvements and a greatly expanding ,knowledge base, have greatly improved the profitability in just the four short ,years since the study. In fact, the question is no longer can a vertical ,farm work but how big can this industry get? and, will this industry ever grow ,more than leafy greens?

CAN THE INVESTMENT SCALE?

Despite being in its infancy, this technology already accounted for one ,percent of Japan's lettuce production in 2014, from 165 vertical farms. While the ,number of farms has increased significantly since then, so has the size ,of the farms. This year, a single farm opened which will supply ,0.6% of the whole Japanese lettuce market. In 2015 the vertical ,farming industry was worth 1.15 billion dollars, in 2020 its projected to be ,an industry worth over 13 billion dollars. Just last year the US firm ,plenty, raised 226 million dollars, with their plan to roll out their farms near ,every major US city. With investment from the world's richest man Jeff Bezos, ,it's a significant statement for the industry. But it's not just the big ,companies. For eighty-five thousand dollars, you can buy a shipping container ,with a fully installed farm inside and it's delivered directly to you. ,this container requires 1% of an acre but can produce 20% of an acres worth of ,produce. This low cost of entry makes vertical farming very accessible to ,entrepreneurs and many are getting involved. A lack of investment certainly ,isn't this industry's barrier to growth. but what about market size? ,any of these operations focus on the premium end of the market because they ,are capable of delivering the highest quality produce but they also focus on ,it out of necessity. Since the bigger profit margins afforded by premium ,products, offset the labor and energy costs of the operation. While this is ,good news for current businesses, plant factories will have to compete on price ,with traditional growing methods, or its ability to impact at a global level will ,be severely limited. Only a small percentage of the market is willing to ,pay a big premium for high-quality environmentally-friendly products. The ,more vertical farming shifts to the right on the graph, the bigger the size ,of the market becomes. For the leafy green market, the cost of production is ,shrinking fast. As of 2018, a number of vertical farm products are cost ,competitive with the market, although many are still sold at a premium to ,enhance profits. Taking a look at a suburban medium-sized farm from Japan ,2015, we can see just how close to market costs they were. They were able to ,sustainably sell at a price just 12 percent above the country's wholesale ,price. Looking into their costs, we get a sense of the opportunity at hand. In fact, the ,cutting edge plant factories are likely to have a cost breakdown that looks more ,like this. Year on year, yields continue to increase for given inputs and the ,cost of the inputs continues to fall. The electricity, depreciation and labor ,costs are falling every year as technologies continue to improve. This means for leafy ,greens at least, vertical farms are in a position to corner the market. If ,vertical farms take over the leafy green market, what impact will this have on our ,global challenges? Lettuce growing uses over nine trillion liters of fresh water ,every year but that accounts for just 0.02 percent of global fresh water and ,lettuce accounts for just 0.1 percent of our agricultural land usage. While the ,leafy green market is more than just lettuce, the reality is it's just a small ,fraction of global agriculture. To make a big global impact, vertical farming needs ,to be able to economically grow a broader range of produce.

we identified plant factories as the most viable version of the vertical farm and saw how it is already technologically and economically viable for leafy greens. However, energy remains a challenge for plant factories, both in terms of cost and carbon footprint, spoiling it's otherwise very positive environmental profile. We also identified that vertical farms would need to grow a broader range of crops to have a beneficial global impact. So why aren't we doing that? To be economically viable in the foreseeable future, plants grown in vertical farms ideally need the following characteristics: high edible mass percentage, low plant height, fast growing cycles, suited to hydroponic growing short shelf life. While these factors are a good rule of thumb for determining the current profitability of a crop. There is one fundamental barrier to being able to grow every crop type. That is electricity. Leafy greens don't require

much light to grow as they are made of around 95% water and their edible mass makes up most of the crop. Compare that to rice crop which provides the most calories worldwide, supplying 19% of global human calories. It is just 15% water and has a much lower edible mass percentage. Unfortunately growing rice using artificial lighting would require about 30 times more energy than lettuce. Rice grown in a vertical farm using current technology would produce extremely expensive rice and have a significant energy demand. Energy is the major constraint for plant factories and the overwhelming factor that dictates what plants can be grown. For this reason, this video series will mostly focus on the energy constraints of vertical farms. I've broken crop types into three broad categories based on their approximate energy requirements.
Phase 1: Leafy greens and Herbs, this is the current phase.
Phase 2: Vegetables, Roots, Pulses and ground fruits, which will require 2.5 times more energy per kilo.
Phase 3: Staple crops, nuts and Tree Fruits with 30 times more energy per kilo.
Energy constraints aside, what impact could introducing each phase of crops have on the global problems.

IMPACT

If vertical farms were to become the sole production method for the phase 2 crops, we could expect to reclaim 2.1% of global habitable land from agriculture. Water is another story. This category of food is highly water intensive, pulses in particular have a relatively high demand for water. Growing this category in vertical farms would save a significant 23% of global freshwater consumption. This change alone could have a profound impact on global water security. Though it's not a significantly greater saving than what could be achieved using hydroponic greenhouses. If we add phase 3 crops, we can expect to reclaim 15.5% of global habitable land. Most of which could be returned to wildlife. Once again with water, the change would be dramatic. Introducing Phase 3 to vertical farming would reduce global freshwater consumption by an astonishing 91%. This would completely transform global water security. (electrical sizzling) Given the huge potential of introducing Phase 2 and 3 crops to plant factories, it's essential to investigate ways to reduce the energy constraint. Without a dramatic reduction in energy consumption, Phase 2 and Phase 3 in particular cannot be realized. So how can we reduce the energy cost of vertical farms? To do this, we need to understand more about yield and how it relates to energy efficiency. Yield is an indicator of a farms operational efficiency.

While it's relatively simple for traditional agriculture, there are numerous ways to measure yield in vertical farms. We will define absolute yield = edible kilo/meter squared surface area/year. We will define footprint yield = edible kilo/meter squared land area/year. An outdoor field only has one level, so the land and surface area are the same. This means absolute and footprint yield mean the same thing for traditional agriculture. For a vertical farm, things are different. Doubling a five layer farm to a 10 layer farm, doubles the footprint yield, because it produces twice the amount for the same building footprint. Absolute yield remains the same however, because doubling the layers doubles the surface area. So which

yield should we measure for vertical farms? A 70 times greater footprint yield sounds impressive but is it a fair comparison? Some critics argue not, claiming it makes their efficiency seem greater than it really is. When talking about land savings, footprint yield is a fair comparison. As doubling the layers of your vertical farm doubles the land you save from displacing field production. However, it's important to remember that doing so would double the energy requirement. If you are using solar to provide that energy,
then doubling the energy would double the solar footprint. This should be factored in when comparing footprint yields. In reality, for most crop types, the area of additional solar panels is very small when compared with the vast land savings of adding more layers to a farm. While the 70 times greater footprint yield seems high, it's only going to get higher in the future. Plant factories can have an arbitrarily high footprint yield, because they can grow as with as many levels as are economically viable. Future vertical farms will likely have a footprint yield hundreds of times greater than the best outdoor farms, this will allow them to leverage a significant economy of scale. While footprint yield is valuable measure of farmland saved, it's not necessarily the best indicator of the operational efficiency for a vertical farm. After all, skyscraper farms would boast very impressive footprint yields, yet would not be profitable. As stated before, the biggest challenge for plant factories, is energy. If doubling the surface area, doubles the energy requirement then it makes more sense to use a measure that is independent of the number of levels in a farm.

For this reason, all future references to yield in this research paper will mean absolute yield unless stated otherwise. With this in mind, how do plant factories increase the yield of a given level? Plant factories that grow produce faster get more harvests per year and increase yield as a result. They can also grow plants closer together in the horizontal dimension, this greater density increases absolute yield. Increasing the edible mass per plant also increases the yield. That is achieved by growing a higher percent edible mass plant or by growing larger plants.

ENERGY EFFICIENCY

Increases in absolute yield for a given energy input, leads to a higher energy efficiency. As such, improvements in absolute yield are vital for plant factories. Energy efficiency can be thought of as the most critical metric in vertical farms. The higher the kilos of edibles mass per watt, the higher the energy efficiency. This metric can be considered the fundamental determinant of what crops can be grown in a plant factory. Not only is it essential for the profitability of current farms, improving this number has a direct result on how much they can positively affect the global challenges. For the purpose of the research, the term yield improvement, it means energy saving.

TECHNOLOGICAL IMPROVEMENTS

Technology in this area is improving quickly, but what can plant factories do to reduce the energy overhead? The key is to maximize the kilos of edible mass per watt of light and also reduce the dollar per watt of electricity. So what changes can be made to improve it?

Vertical farms can increase the yield of any given plant beyond what is seen in hydroponic greenhouses. And it's not just because of their additional growing layers. They have much greater temperature, atmospheric and light control than greenhouses. This allows for superior growing conditions and waste elimination. Plants only absorb certain wavelengths of light. Using LED grow lights allows plant factories to use specific light recipes tailored to each plant, enhancing the energy efficiency. While a vertical farms, atmosphere, nutrient and light control already far surpass current growing methods. There are many opportunities to increase it further. Plant growth is complex and affected by many parameters. There is still a considerable amount of work to be undertaken to understand the optimal conditions for plants. Outdoor plants use changes in sunlightto determine when to grow and flower. Normally this is dictated by the environment but LED's can emit different recipes of light at different growth phases of the plant.These light recipes can alter many of their characteristics. They can be tailored to increase the flowering portion, reduce the root growing phase and even control how the plant tastes. This allows plant factories to increase the edible mass percentage significantly. Energy a plant uses building none-edible structure is waste energy. This is inconsequential for sun grown plants but is critical to vertical farms. Field grown lettuce has about 40% edible mass when considering root systems and inedible outer leaves, while vertical farms have managed to achieve 92% edible mass. But that's not the only advantage of light recipes. Since they can be used to trigger growing cycles, they can accelerate plant growth considerably. While field grown lettuce can be harvested twice per year, vertical farms can harvest up to 12 times per year. Even rice can be harvested about four times more often than when grown in a paddy field. While the edible mass percentage for lettuce is approaching its limit,that's not necessarily true for other plants. Despite being a new industry, yield improvements are happening quickly. This is partly due to new possibilities with data analysis. Vertical farms have a multitude of sensors measuring many parameters. From, temperature, to nutrient levels. The plants are analyzed with cameras and sensors which monitor plant health in real time. Because plant factories control the environment so effectively, it's considerably easier to actively run experiments and interpret the data. Maximizing yield by the fine tuning of variables such as CO_2 and humidity levels. Not only that, but due to having considerably more harvests per year, they have a lot more opportunities to experiment, collect data and learn. This allows for a learning rate that is a number of magnitudes higher than other growing methods. As a result, vertical farms are hiring data engineers and sensor specialists as a significant percentage of their workforce. Artificial Intelligence already plays a key role in many vertical farm operations. Despite this, it's still at an early stage. As sensors continue to get cheaper and more capable, the opportunities for vertical farms increases considerably.

SEEDS

A number of plants are poorly suited to vertical farms, due to low edible mass percentage, being ill suited to hydroponics, or being a tall crop. Since, current commercial outdoor crops have no need to consider these parameters they breed plant varieties that thrive outdoors and are often incompatible with vertical farms. Plant Factories have different priorities and require different seed types as a result. There are many dwarf varieties of existing crops, that could be utilized. If they can match existing crop quality with a seed optimized for short height, hydroponics and high edible mass percentage, then the energy requirement for replacing existing crops could shrink significantly. Additionally, seeds can be bred for faster harvest cycles, not a requirement for most current crops. Many current crops sacrifice breeding for peak yield so as to breed for vital resistances. This isn't necessary in vertical farms because of their sealed conditions. Unlike greenhouses, they don't need to vent and are run like a clean room environment. These yield improvements alone can significantly reduce the energy gap for future crop types, but it's not the only improvement available. This area has a huge potential for improvement, especially for plant factories that utilize genetically engineered seeds. Gene editing techniques are getting much cheaper and easier to implement. This has a lot of potential for both indoor and outdoor farming in the future.

EFFICIENT LIGHTING

In the last few years LED lights have improved considerably. Special units are being developed specifically for indoor growing and their efficiency is anticipated to improve by 50% in the next decade. Efficient LED's run colder, not only does this save electricity but allows them to be placed closer to the plant without risking heat damage. This allows plant factories to fit more levels into a fixed building height, increasing footprint yield. Closer positioning increases light penetration into the canopy allowing plants to be grown closer together and increasing absolute yield. It also reduces light bleed and increases light absorption efficiency, reducing energy requirements. Greater use of reflective bay materials, deeper penetrating green wavelength light and mid level bay lighting can further reduce the total energy requirements. It's not just efficiency though. LED's are increasingly capable of delivering a broader spectrum of light, allowing for greater control and yields. The cost of the units are also falling quickly, while the unit lifespan continues to improve. This will reduce the the depreciation costs for future vertical farms, and is essential for improving their cost competitiveness. If there is one technology that could transform the potential of vertical farming, it's renewable energy. It has the potential to solve the environmental and economic outlook simultaneously. Solar for instance is projected to half in cost over the next decade. This will bring its cost below traditional production methods in many areas of the world. Reducing the cost of electricity will be the final step, enabling vertical farms to grow a broader range of products. The future of energy production is looking very promising and is of critical importance to many global challenges, not just those related to vertical farming.

The Future of Vertical Farming

we identified energy consumption as the primary barrier to plant factories having a big impact on the world and learned how vital improving absolute yield is to improving their energy efficiency. We also looked at a number of ways that future vertical farms can boost yield, lower their energy consumption, and take advantage of cheaper, cleaner electricity. But when will these improvements happen, where will they happen first, and how far can the improvements go? When can we expect vertical farming to change the world?
There's no single point in time where this technology becomes viable to grow everything everywhere. The economic viability of the industry will vary by crop and location at any given time. Let's start with phase one crops.
Phase one is already well underway in Japan for instance. But just because it's viable there doesn't mean it's viable everywhere. We can estimate where this industry will make the most economic sense, by looking at what percent of vegetables a country produces as a ratio of it's total vegetable consumption. Countries that import high percentages of their vegetables probably do so because producing it locally is difficult and expensive, resulting in high market prices. We also need to consider the local cost of electricity, as it's one of the fundamental costs for plant factories. High electricity prices would make food produced in vertical farms prohibitively expensive. Taking the two factors together we can produce this map. Given that Japan has the most mature vertical farming industry,
we can use it as a control and ask which countries have similar or favorable economics. The map shows a very promising picture. Countries similar in color, or greener than Japan, are likely to have the same or better opportunities. In population terms, 66% of the worldhave a more favorable economic environment than Japan. With a further 29% having at least similar economics. In the green regions, phase one crops are likely to have a high profit potential right now. On an environmental note however, this analysis assumes current energy production and could be expected to incur a carbon cost, at least with today's energy mix. Though, given phase one's relatively small scale and energy requirements this carbon cost is low.
Phase 2 would require approximately two and a half times the energy of phase one. Let's model this energy requirement
into the best current vertical farms. If the economics are as calculated, phase two crops are more or less viable right now, although profits on non premium products will be very slim. However, if we situated the vertical farm in a green region, it's profitability would be much better. In fact, we are already seeing the emergence of phase two crops such as cucumbers, tomatoes, and even strawberries being produced commercially in these regions. That said, expect to see a high emphasis remain on leafy greens for now, as the profitability is much better. If phase two continues its course and becomes ubiquitous worldwide, we will start to see significant global freshwater savings in the next 10 years. At this point, the global benefits of vertical farms become a lot more tangible. Still, the energy problem only becomes bigger if phase two farms reach a global scale. While it's not a risk to global energy capacity, the carbon cost may be prohibitive if renewable sources aren't used.
Phase three will have the greatest global impact but it's also the hardest to achieve for this technology. A significant part of phase three production would be staple crops such as rice and wheat. Current production of these crops already benefit from a massive economy of scale and have small profit margins. They are also classed as commodities, as such, there is

little benefit from the high quality product that vertical farms can achieve. Staple crops store well, thus neutralizing the freshness value that vertical farms provide. Additionally, staple crops are generally tall, which hurts the growing density advantage of plant factories. However, the biggest barrier of all is the 30 times
greater energy requirement compared to leafy greens. With all these obstacles, it's worth asking if phase three is even remotely feasible. If it is, what would it take to make phase three viable?

Well, there's no reason that a vertical farm couldn't grow at a significant economy of scale. Surprisingly, commodity crops ability to keep may actually be an advantage for vertical farms not a hindrance. Plant density and large energy costs are much bigger problems. To make phase three profitable, the energy cost per kilo must be greatly reduced. Let's assume that in order to be profitable, energy costs can be no more than 25% of retail price. Rice is the largest provider of global human calories, let's use that as an example. In the U.S. in 2016, rice had an average retail price of $1.52 per kilo. That gives a maximum energy cost of 38 cents per kilo. We will model a yearly output equivalent to a large vertical farm at 1,000,000 kilograms per year. The state of the art Techno Farm in Japan, produces one kilogram of lettuce for 5.7 kilowatt hours of electricity. At a cost of 11 cents per kilowatt hour, one kilogram of lettuce costs 63 cents of energy per kilo. A study of plant biopharmaceutical suitability determined that rice grown under artificial light required 31 times more energy per kilo than lettuce. This is where the 30 time energy factor for phase three comes from. If we multiply the energy cost per kilo of lettuce by the energy factor required for rice, we get an energy cost per kilo of $20. This is a massive 52 times larger than our 38 cent max energy cost. It's such a huge factor that it seems insurmountable. But a closer inspection of the rice experiment reveals some opportunities. Plant factories have had over a decade to create the perfect conditions for lettuce, if the same can be done for rice, then we will be able to significantly shrink the 31 times energy factor. So let's take a look at that. Before we go any further, remember that increases in absolute yield for a fixed energy input translates to an energy saving. For example, a 33% yield increase translates to a 25% energy saving. All yield increases will be calculated as energy savings for this analysis. To start with, a much denser crop needs to be used. Field grown rice is typically over a meter tall. Plant Factories will need to use a dwarf variant of rice plant. Both short in height and high harvest index are essential. If the edible mass percentage of the rice plant can be increased to achieve just half the improvement seen in lettuce, then we can expect a 23% energy reduction. In the experiment rice was grown under 400 parts per million of CO_2, or normal levels. Increasing the CO_2 concentration to 1,200 parts per million, we can expect a 26% energy saving. Further optimization of the nutrient and light recipe will likely increase the yield and shrink the cultivation period saving a further 20%. The rice experiment was conducted at 25 to 27 degrees Celsius. Higher temperatures increase the growth rate of rice, with 27.5 to 29.5 degrees C being optimal. The faster growth rate shortens the cultivation period and allows for a 12.5% energy reduction. It also used 12 hours of light and 12 hours of dark. Other experiments have found that shorter hours of daylight such as 10 actually encourage early flowering. This not only reduces the daily energy requirement but further reduces the cultivation period saving as much as 20%. We are now 16 times our maximum energy cost of 38 cents. Much better but still far too high. Therefore, we will need to look elsewhere for improvements. For phase one and two, there is significant freshness advantage in placing production close to consumption. For phase three, it's much less important. In vertical farms, rice can be produced anywhere and shipped everywhere without a freshness penalty. This means they can be placed in regions with cheap electricity. Since rice can be stored indefinitely, it can be transported by boat not aeroplane, helping keep its transport emissions very low. The rice electricity cost is based on 11 cents per kilowatt hour. However, if we can move our vertical farm anywhere, we might as well put it somewhere with cheap electricity. The farm would need its own energy supply to ensure the cheapest possible energy. A 62 megawatt solar array in Mexico can produce electricity for 1.97 cents per kilowatt hour. The farm will need a 20 megawatt system scales to 2.67 cents per kilowatt hour. Because solar energy isn't consistent, it will also need an energy storage system. Even factoring this in, we could expect an energy cost of 3.14 cents per kilowatt hour. By relocating our vertical farm, we can reduce the electricity cost by a staggering 71%. This is only possible due to remarkable progress with renewable energy. Despite a magnitude reduction in energy cost, we are still looking at $1.74 for a kilogram of rice. This is prohibitively expensive at five times our target cost. Technology isn't static however. Current phase one farms are only profitable now because of significant improvements over the last few years. So if we factor in technological progress, will we be able to close the energy gap? Absolute yield is set to increase dramatically because vertical farming is a relatively new technology and also because the combination of highly controlled growing conditions, numerous sensors, artificial intelligence, and rapid cultivation periods greatly multiply the learning rate of vertical farms. If we model our yearly absolute yield increase relative to outdoor farms, we can save the difference in energy costs. From 2018 to 2030 we can expect an absolute yield increase of at least 32% relative to outdoor agriculture. That equates to a 24% energy saving. Before, I mentioned the dramatic improvement in LED's efficacy. This graph shows the predicted energy reduction due to LED improvement from 2018 to 2030. In total it represents a 43% reduction in energy costs. This improvement is based on PC LED technology. Other LED technologies have a much higher performance ceiling and will likely provide greater energy savings by 2030. The greatest technological cost reduction will come from solar. Whist being a clean source of energy, it's also on track to become the cheapest bringing us closer to an energy revolution. From now until 2030, the cost of solar is predicted to fall by 56%. So what happens when we stack absolute yield, LED, and solar improvements together? This synergy creates a powerful multiplier. The model predicts a profitable energy cost for rice by 2029. That leaves a decade to fix the other potential problems in advance, such as breeding a suitable seed and learning the optimal conditions for vertically farmed rice. Having looked at the current state and the future technology trends, it's hard to argue it isn't here to stay. While this isn't going to happen immediately, growth in the sector will accelerate as technological improvements drive down investment and operational costs. Vegetables produced in a local vertical farm will likely be a common sight in supermarkets around the world, perhaps as soon as five years, maybe 10. Most sources suggest crops like rice are over 40 years away, or simply not possible due to the energy constraint. However, most estimates appear to overlook the extreme technological progress and how it can affect this industry. Taking these changes into account brings their viability a lot closer to present day. Whether it's 10 years, 12 years, or 15 years, solving the energy problem seems inevitable.

LIVESTOCK FEED

Human consumption only accounts for 55% all crops grown. 9% is used for biofuel and 36% is used as livestock feed. Meat takes a huge amount of water to produce, as the crops grown for the animals require a lot of water. Producing one kilo of beef requires seven kilos of crops to produce. This makes meat production extremely water inefficient. It's not just water though. Meat production is also extremely land inefficient. 70% of all agricultural land is considered grazing land. So if we really want to return a significant amount of global land back to forest, we need to substitute meadows for an alternative food source. Currently, foods such as soy and hay are used to supplement livestock feed. However, they are land intensive to grow. Soy is also a highly water intensive phase three crop, meaning we are at least 10 years away from being able to grow it in plant factories. Meat production contributes a considerable amount of the global challenges but it's largely due to its food import. Sprouted barley fodder can supplement a significant percentage of livestocks' feed and can improve the health of the animals. It can be grown extremely cheaply in plant factories, with minimal labor, water, and electricity costs. In fact, the energy costs are so low, that it can be grown profitably right now, all across the world. While data for this market is limited, it appears to be growing quickly. If this opportunity is realized by businesses globally, we will start to see an impact on the global challenges sooner than expected.

CONCLUSION

If we make the necessary changes, what will our 2050 world look like? We are looking at a world with a highly resilient food production system. That scales easily to produce more food and not be vulnerable to climate, flooding, and pest damage. A system that will make food cheaper than it's ever been before. It's not the only change required to eliminate world hunger, but it will help significantly. Reducing agriculture's global fresh water consumption by 91%, will have an even greater effect, both in terms of global water security and environmental impact. We may be able to halt and reverse desertification, and drastically reduce most of agriculture's large greenhouse gas footprint. We could further help reduce atmospheric CO2 by reforesting the 15% of the global land we are able to displace. And this will finally reverse the trend of mass wildlife depopulation we see today.

For these global issues at least, the news is promising but more changes and technological improvements will need to happen to solve them entirely. While we can probably expect a large positive impact, these changes won't happen overnight.

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