LABORATORY

SOIL WATER INTERACTIONS

- Soil: material in the top layer of the surface of the earth in which plants can grow.

is non renewable because generated from rock processing, so it takes long for soil to generate. Our welfare depends on soil and climate.

- Land: solid part of the earth's surface.

- What do plants need to grow?

- Solar energy.
- Fertile soil.
- Water.

- Users of soil: people transform landscapes to obtain food, fiber, timber and ecosystem goods. Land appropriation has the main consequence of its use for primary production for human consumption, as stated by Vitousek.

83% of land surface is directly or indirectly affected by human influence according to Sanderson.

proportions of landscape: the more we go towards intensification the more intensive agriculture, protected land and urban settlements take place:

we might think that the biggest change for a land is urbanization, but that might not be true because urban cities cover only a small % of the landscape.

when we convert lands we start from the forests, usually from mining. People will start deforesting more for agricultural purposes, then through population growth we move forward intensive agriculture. By this transition we can change the soil through:

- Erosion: we remove a big part of the soil that contains the organic material.
- Agriculture: through the fertilizers we change the properties of the soil, in fact they contaminate the underground water.
- Current land use: 33% is agricultural.

the transition towards agricultural use of land has reduced forests lands by 20%-50%.

- Planetary boundaries:

imagine to have a system where alteration is the consumption of the resource, degradation is the response of the system:

At a certain point degradation will increase reaching a point of maximum in a non stable way. Because of this instability the way back will be different from the way forward:

we have 9 boundaries, 6 of them are superated:

- Climate change
- Biosphere integrity
- Land system change
- Freshwater change
- Biogeochemical flows
- Novel entities

- Soil layers:

  surface is the most organic one.
  mineral increase organic decrease going downward.
  subsoil: bad rock.
  the first 2 layers are those where plants grow and they are also the fertile ones.

- Fertile soil properties:

Minerals are macronutrients for plants. Their main nutrients of fertile soil are N, P, K. The organic fraction gives soil the structure and the capacity to absorb moisture. Plants usually require acidic soil and a structure that can retain water but at the same time drains it if it's too much. Finally the biotic factors are those who analyse the presence of microorganisms.

- Nutrients: we need all of them. In this case we need to take into account the Liebig law. If a "barrel" disappears, then the yield is not full.

Nitrogen: plants need protein to build up their structure. Nitrogen is a key component of amino acids, which forms proteins and enzymes.

Phosphorus: it increases the resistance of the plants. It is needed the most by flowering and fruiting vegetables. It can also speed up maturity, help the fruit formation and stimulates roots growth.

Potassium: it increases resistance especially at cold T. It is more needed by root vegetables.

- Soil and water cycle: the movement of water into the soil depends on the soil itself, which determines the space in itself and for water to move. We have gaps that can help the water circulation if related, but, if isolated, water gets stuck in them.

- Porosity: is the volume of the empty spaces present in a rock or soil:

  It can vary from 0 to 1. 0 means free of pores, so only solid. 1 only pores land.

- Void index:

- Effective porosity: ratio between the volume of water released by gravity from a sample of soil perfectly saturated and the total volume of the sample.

- Permeability: ability of the medium to let water pass through it. It is measured as a speed. The finer is the sample, the lower is the permeability. The most rapid water movement is in sands and aggregated soils.

Darcy's law: imagine a box full of a medium. If there is no medium the equal level would be reached instantly. But if there is a medium there is also a dependence of time:

K= permeability. Dh/L is geometry.

- Capillarity: ability of a liquid to flow in narrow spaces without the assistance of external forces. It is due to pressure and cohesion and adhesion.

- Soil water movement:

- Infiltration: movement of water from soil surface to soil.
- Capillarity rise: movement from saturated zone upwards unsaturated ones.
- Recharge: movement of water into saturated zones.
- Percolation: downward flow in unsaturated zone.

- Water potential: we can use the 1^{st} and 2^{nd} principles of thermodynamics in the hypothesis of perfect gas:

1^{st}: 2^{nd}:

U= total energy; L= work; Q= energy; p= pression; dV= volume variation; S= entropy.

Gibbs found and called u+pdV= ELETROCHEMICAL POTENTIAL.
Then we can have also the HYGROMETRIC POTENTIAL :

the water potential of the soil is a negative pressure and expresses the work plants must fulfill in order to extract water from the soil.
problem: water evaporates in the atmosphere: the potential decreases from the root to the leaves.
we have different types of water potential:
G: work needed to keep water at a certain height under the action of gravity.
P: is typically 0. It is determined by the pressure imposed by the H20 soil.
M: determined by the forces of attraction between water and soil matrix.
S: determined by concentration of solutes in water.

- Field capacity: amount of water remaining in the soil days after having been wetted and after free drainage has ceased. The matric potential at this conditions is -01 to -0.33 bar.

- Wilting point: water content of a soil when most plants growing in that soil wilt and fail to recover. No more water is available to plants.

- Total available water capacity TAW: water that can be absorbed by plant roots.

TAW= FC-WP

FC= Field Capacity.
WP= Permanent Wilting Point.

<u>SOIL WATER BALANCE</u>

- Soil water content:

- MAD= Maximum Allowable Depletion

what happens below MAD? We normally measure it with a water stress coefficient and assume that the crop, instead of evapo-transpiring ET, evapotranspires KsET.
Ks is a coefficient that can go from 0 to 1 and is constructed to be a linear coefficient. It goes from 1 to 0 once the wilting point is reached. Ks is also called water stress coefficient.

- Soil water balance: we take a portion of a field and examine water fluxes.

We can se that if we are above field capacity we have deep percolation.
if the soil is not able to drain with deep percolation then we have surface runoff, which is not properly vertical, but we'll assume it is.
variation in soil moisture level= P + R + C – I – EvapoTrans. Where P= precipitation; R= runoff; C= capillarity; I= infiltration.
C negligible.
R negligible because only vertical.
I is for us deep percolation.

<u>EVAPOTRANSPITATION and CROP COEFFICIENTS</u>

- Crop Water Requirement=CWR. It is the amount of water required to compensate the ET loss. So we can have the CWR that refers to SUPPLY, while Etc (evapotransp. Crop) that refers to LOSSES.

- What drives ET?

- Climate: warm climate need more water for crops than in a cool one.
- Crop type: maize and sugarcane need more water than millet or sorghum.
- Growth stage of crop: fully grown crop need more water than crops just been planted.

- Equations for ET: we can use the Penman-Monteith equation:

  reference surface: resistance depends on crop height, ground cover, LAI and soil moisture. LAI is the Leaf Area Index, so the index of density of vegetation divided by the area it occupies in the ground.
  The reference surface resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with the right amount of water. These are characteristics that result from the hypothesis of 1D fluxes upwards.

  to achieve ET0 (reference ET):

  Note that ET0 is a climatic parameter, independent from crop and soil.

  how to move to crop-specific ET?

  We can have 3 different values of Kc related to 3 growing periods:
- Seeding of the plant to first leaves: low Kc initial constant.
- Reproduction of the plant: increase Kc till it arrives to medium Kc.

- Kc decreases linearly till Kc end.

SURFACE IRRIGATION

- Surface irrigation: water is applied and distributed over the soil surface by gravity.

flood irrigation: water in uncontrolled and inherently inefficient.
surge irrigation: in this case there is a significant degree of management, in which we manage geometry.

- Process of surface irrigation: the quantity and frequency of it depends on different practices and factors. We let the water runoff from the application point to the end of the field. We have 4 phases:

- Advance: water advances on the field length.
- Storage/wetting: starts when the water reaches the bottom end of the field and ends when inflow is shutoff. Water starts runoff.
- Depletion: period after shutoff when field is submerged.
- Recession: water front retreats towards downstream end.

during the process we can have water losses in the canal due to evaporation (2-3%) and seepage (infiltrazione nel suolo, 97-98%). Due to seepage we can have:

- Percolation: continuous saturated flow zone between canal and water table.
- Absorption: saturated zone around canal and above water table, unsaturated flow in between.

we can also have water losses in the field due to deep percolation and surface run off + soil evaporation:

How can we reduce water losses in the field?
- Tuning (accordare) time of application.
- Increasing/partitioning the applications point, so water has to expand into shorter distances.

How to limit soil evaporation losses? Through maintenance of pipelines and connections.

- Soil arrangement is the way soil particles and components are organized or structured since they influence how water is distributed, infiltrates and moves across or into the soil during irrigation.

application by gravity: it refers to the setup of soil surface/subsurface to facilitate the distribution and infiltration of irrigation water under the force of gravity and it can be:

- Basin irrigation: it covers small areas and level surfaces surrounded by earth banks (argini di terra). Water is applied rapidly and infiltrates. The basins are linked sequentially so upstream drainage feeds downstream plot. It is good in soil with low infiltration rate. This kind of irrigation is common for rice and wheat.
- Furrow irrigation: is a surface irrigation method where water is applied through small parallel channels that run along the length of the field, typically aligned with the predominant slope. Each furrow is supplied with water at the top end, utilizing systems such as gated pipes, siphons and head ditch or bankless systems. Factors in speed of water movement: slope, surface roughness, furrow shape, inflow rate, soil infiltration rate. Factors

in furrow spacing: crop species, machinery, and the common spacings are between 0.75 and 2 m to accommodate different crop requirements. In this case steeper (ripidi) slopes increase water speed, but require management to prevent erosion. Rougher surfaces slow down water flow, which can impact distribution and uniformity. High infiltration soils may require slower water application rates to ensure even distribution. Crops are planted on the ridge (crinale) to avoid roots saturated soil for too long. Usually there is one or more crop rows per ridge and the furrow length is usually < 100 -200 m. Short furrow usually generate more uniform water application, but higher risk of runoff losses.

What water does is to flow in the furrows and spread in the ridges by infiltration.

- Surge irrigation: variation of furrow irrigation to improve application uniformity. In this case water supply is pulsed on and off in planned periods. Wetting-drying cycles reduce infiltration rates through surface consolidation and soil particle disintegration. In any case there is the risk for clay soils of sealing.
- Border strip irrigation: is another surface irrigation that combines features of previous ones. It's an hybrid of basin and furrow. The field is divided in bays or strips of 10-70m*100-700m. Note that also in this case banks help water flow control and prevent it from moving laterally. Water is applied to top end of the bay and this kind of irrigation is typical in the case of pasture irrigation.

- Compartments:
- Clearing (spianata):
- Border:
- Campoletto:
- Simple wing:
- Double wing:

- Irrigation by infiltration is a not strict irrigation system because not above the ground. It delivers water through pipes in the ground.
- Design of open channel:

<u>SPRINKLER IRRIGATION</u>

- It simulates rainfall and water is distributed through pipes by pumping and sprayed through sprinklers. Usually suitable crops are row, field and tree crops, but not delicate ones. It is adaptable to any slope since it is a pressurized system and facilitates the leveling of the soil. Suitable soils are the ones with high infiltration rate.
- Pressurized system: water has to pass through noodles before going into the soil surface.
- Layout of the system: it's pressurized so we need unit, pump, unit to make it go under pressure. The main line is the main pipe line that crosses the field. The main aim of the main line is to transport the water and connect it to the laterals. Laterals are pipe lines that aim

permit to cover the whole area and they cross the field orthogonally. The final part is the sprinkler, which are installed for each lateral. As soon as we go to the end of the lateral the water decreases and arrive to the soil thanks to the sprinkler (circular sprinkler).

idea is that during the lateral there is a decrease of the water it transports.
laterals provide water into the field that needs irrigation.
if we have sprinkler that needs to send part of the water to left and part to right, then water will split inside of the sprinkler.

- Pump unit: we need hydraulic pressure. We can use different types of pumps. 90% of the pumps are centrifugal pumps, where usually Z is <8m. In case water source is the ground source, then the elevation we have to guarantee can be higher than 8m. If we want to take water more in depth of the soil, what are the pro and cons? It is possible to withdraw water from lower conditions but we need to do a trade off between the energy and costs needed. Pump requires fuel, energy, so as soon as we want to take water from deeper then we will have major costs.

- Pipelines:

- Main line: deliver water from pump to lateral. It can be permanent or temporary and can be moved. Typically in concrete, plastic and alluminium.
- Laterals: deliver water to sprinklers. More often they are temporary or portable. Typically made in alluminium or plastic.

solar energy considered as electric it's the main used in this pump.
when we withdraw water from rivers we will have smaller pumps. As soon as water enters into the pump than it enters into the main and sub lines.
material usually are plastic or aluminium more than concrete.
the line can be fixed in the field or moved. The advantages of moving the system are that if there is a problem in a part of the system we just have to substitute it without removing the whole system.
laterals generally are not permanent in the field. They have to be not too heavy to be transported, and not damaged (so mainly made of plastic).
pipelines: we transport water under a certain pressure, but as soon as we arrive at the pipelines we have an hydraulic loss. The final part of the system, sprinkler, bases the covering of the field on the pressure, so if the pressure changes than changes also the area covered from the irrigation. Hydraulic losses are distributed in the pipelines and they depend on the section of the system, material and diameter mainly. We should minimize these losses, because the differences may be very high between the first and the second sprinkler. As soon as we know how to install our system we know which losses we do have.

- Couplers: connect different pipelines and joint elements between pipes. They help to put together the pipelines without having lacks. These systems are portable so they need to be light, they should be reusable and flexible as well as non corrosive and durable.

- Sprinkler head: has the aim of distributing the water in the field avoiding percolation and runoff. In general they are fixed on the base and the head can rotate or circulate. In order to properly work sprinkler has to have a certain pressure (10-70m; 16-40m). Higher pressure means higher area we can reach. Its characteristics are exercise pressure, flow, range, rain intensity, hour rain height, pulverization index efficiency.

exercise pressure can be low (0.5-3bar), medium (3-5bar) or high (>5bar).

rain hour intensity: it has to be not too strong to ruin crops and not for too long and expensive because of energy.

instantaneous rainy height:

- Other accessories:

- Water meters to measure water delivery.
- Flanges, coupling, nipples.
- Pressure gauge to monitor pressure.
- Fertilizer applicator.

- Portability classes:

- Portable: portable main lines, laterals and pumping plant.
- Semi portable: fixed pumping plant.
- Semi permanent: permanent main lines and fixed pumping plant. Only portable laterals.
- Solid set: laterals fixed for the season.
- Permanent.

- Sprinkler systems layouts:

- Center pivot:

- Linear move:

- Traveling big gun: inefficiency because the area close to the sprinkler is not covered fully:

- Side roll.
- Advancement scheme efficiency-overlap effect. We need to be careful because too much overlapping means too much water.

The design of the system is provided on the amount of water withdrawn but it happens that the irrigate more water than needed by the crop, so some is lost. If we apply more water than the field capacity then the soil is not able to store water so we have water loss. With the layouts we need to be sure that all points receive uniform water, especially on intersection points where we might need to provide more water than needed. The efficiency of surface irrigation systems is 50%, the rest is lost because of evaportation. The efficiency of sprinkler irrigation systems is 75%.
When we choose a sprinkler system we need to fulfill the criteria of crop, for the water demand, shape and size of the field, topography of the field and time and labor required.

When we want to size a sprinkler system we have to look at the sprinkler system capacity that depends on peak crop water demand, crop rooting depth, soil type and pumping capacity.

Advantages of sprinkler irrigation:

- No conveyance channels, so no losses compared to channels.
- Suitable to all soils except clay because of the low permeability rate and because its water velocity causes soil erosion.

- Suitable for crops with high density.
- Higher efficiency and so water savings.
- Closer control of water application.
- Mobility.
- Occupies less land.
- Better climate effects.

Limits:

- Uneven distribution with high winds.
- Evaporation losses with high T.
- Very low permeability soils not suitable.
- High capital expenditures.
- Complex design.

<u>DRIP IRRIGATION</u>

- Water is delivered directly to the base of each plant in small, frequent and precise quantities, so we have the highest efficiency. Water continuously drips to the roots through gravity and capillarity in 2 ways:

- Onto the soil surface.
- Directly into the root area.

- We need a system of pipes and tubes that requires also a second control.

- Soils:

- Medium heavy soils: prevalent lateral movement.
- Sandy soils: vertical movement.

- Water goes down in a vertical way.

- First examples of drip irrigation systems are in China and South America. We have a crop made of layers and keep them full of water. Soil has a permeability, so it's porose.

1860 Germany: we have modern drip irrigation, in which we have subsurface irrigation with clay pipes in a way we can have both irrigation and drainage.

- Today the scheme is: water source pump that lifts the water set of hydraulic components (among these filters to clean the water) injectors for fertilizers and pesticides after all this preparation system, we start distributing by laterals the water to the field.

types of filters:

- Screen filters: water flows inside the filter and the outline pipeline is connected to the field. They have flexible or rigid screen to separate fine particles.
- Media filters.
- Disc filters: stacked discs (dischi impilati) of filtering screens with pipe in the middle. Water flows from/to internal to/from external pipe.

backflow prevention device: device that allows water to flow only in one direction. It prevents water to flow from drip system back into the water supply. They occur when pressure in the irrigation system is higher than in supply system.

pressure regulators: they are the opposite of backflow devices. They bring pressurized flow to desired pressure.

pipelines:

- Main and submain lines: typically buried in PVC.
- Hydrants: deliver water to mainfolds.
- Manifold: on the surface and in hard PE.
- Dripper laterals: made in soft black PE tubes along plant rows.

drip emitters: made in high quality plastic, mounted on soft laterals, dense spacing. Water enters at 1bar pressure and exits at 0bar. We can have distinctions depending on the pressure dissipation system: orifice or long path. Another distinction is made in function of the connection to lateral: on-line, in-line.

alternatives to lateral and emitters are:

- Drip tapes. They are integrated drip lines with built-in drippers.
- Porous wall pipes. Typically used for underground applications.

- Irrigation scheduling: the root zone is only partly wetted. Soil moisture depletion is < 40% TAW at the final stage and 20% at the initial one.

- Use of drip irrigation:

- Intensive cultivations of row crops. In this case we have very high capital and operational expenditures.
- Higher density plants: we have one lateral each 2 rows or crops planted in double rows.
- Lower density plants: ensure wetting as much root volume as possible.

- Advantages:

- More effective fertigation, losses are minimized.
- High efficiency: we have evaporation and percolation reduction, so water savings.
- Disease prevention.
- Field levelling not needed.
- Easy to implement also on irregular shaped fields.
- Suited for recycled non potable water.
- High monitoring of soil moisture.
- Lower sensitivity to soil type.
- Less erosion.
- Uniform water application.
- Lower labour costs.
- Supply can be regulated.
- Lower pressure so lower energy costs.

- Limits:

- High initial costs.
- Higher waste.
- Clogging.
- Extra clean up costs after harvest.
- Requires more study and preparation.
- Salinity: not suited for irrigation with saline water.

AGRIVOLTAICS

- Water, energy, food nexus:

Target 7.1 of the SDGs: by 2030 ensure universal access to affordable, reliable and modern energy services. This means we nee to bring down GHG emissions from the energy sectors ideally to reach the 0% emissions in 2015.
What do we need to do? Remove all 37GTCO2eq we are meeting yearly. How can we do it?

- Through renewables accounting for 25%.
- 25% through energy efficiency.
- 20% through electrification. This is the major player since of the global emissions of CO2, 16 billion tons are coming from electricity, and 9 from transport.
- 20% through carbon storage.
- 10% through hydrogen which does not implement the use of coal.

In 2021, 71% of the global population had access to clean cooking fuels and technologies. In 7 of the 20 countries with the largest deficit (sub-saharian Africa), only the 10% had access to clean fuels in 2015.
Even if we are seeing and increase of clean energies, still we have big deficit especially in the least developed countries, and here the deficit is even growing.
What are globally the Water, Energy, Food nexus challenges?

On the energy side we just talked about it. On the food sector we need to increase the capability and supply coming from it, because population is increasing and dying. The major issue here is the land suitable for agriculture, which is the one used for food production. Now we are probably in a situation in which land is very low productive, probably because we already have finished the suitable lands.

On the water side we are facing severe water scarcity, so there is an unbalanced situation between the demand and the supply. Water need time to recycle, so, even if theoretically is a infinite resource, we have to define it finite now, because we are overusing it, leading to a phenomena in which people have scarcity of this resource.

What we can see is that all of this issues have their playground on lands.

- Clean energy sources and strategies:

- Solar: due to technological trajectories sei in motion by past policy, a global irreversible solar tipping point may have passed where solar energy gradually comes to dominate global electricity markets, without any further climate policies.

  The PV panels efficiency depends on:
  Irradiation
  Air T

Wind Speed
Relative humidity

efficiency is a function of local microclimate and is maximized with high irradiation, medium T, slow winds and low relative humidity.
Of the global ground mounted PV plants are:
7% in tree cover areas;
12-17% in agricultural areas;
4.5% in protected areas.

it is relatively easy to build solar plants, that's in fact one of the advantages. With wind is a little more complex.

- Agrivoltaics: they use agricultural land to simultaneously produce agricultural crops and generate PV electricity. But what are the pros and cons?

  CONS: we have a reduction of crop irradiation, South-North disposition maximizes PV efficiency, but creates heterogeneity in soil radiation, plus they may work only for shade resistant crops.

  PROS: panels at 4-5m minimize shading. The orientation at 45° SW or SE lead to homogeneity. Yields do not decrease dramatically. If we use the same land for 2 productive activities then we increase the land use efficiency.

  LER= Land Equivalent Ratio= indicator of land productivity to assess the value of mixed cropping systems:

  thanks to the agrivoltaics we can create specific microclimate able to boost energy and food resilience in climate change context. The vegetation reduces heat storage into soil, increases latent heat exchange and minimizes sensible heat flux thanks to evapotranspiration. PV shading protects crops from high irradiation and reduce water consumption. Agrivoltaics increase production in dry lands also for non-shade resistant crops.

  what are the positive impacts on ecosystem services?
  CO_2 absorption and sequestration.
  Biodiversity conservation.
  Soil erosion prevention.
  Soil fertility maintenance.
  Pollination.
  Aerosol reduction.
  Human thermal comfort improvement.

Riassunto

Main Themes and Concepts

- Solar Energy's Role in the WEF Nexus
  - Solar energy plays a crucial role in achieving sustainable energy goals (e.g., SDG7) by providing affordable and reliable electricity while supporting agricultural and ecological systems.

    - The adoption of solar photovoltaic (PV) technology has reached a tipping point, making it a dominant force in electricity markets globally.
- Agrivoltaics: Definition and Potential
    - Agrivoltaics refers to the dual use of land for agriculture and solar power generation.
    - This approach leverages synergies between crop growth and PV energy production, particularly in water-scarce regions or drylands.
- Efficiency and Land Use
    - PV panel efficiency depends on local climatic conditions, including irradiation, temperature, wind speed, and humidity. These factors also influence agricultural productivity.
    - Integrating PV systems on croplands can improve land use efficiency and reduce conflicts over land allocation for energy vs. food production.

Benefits of Agrivoltaics

- Improved Land Use Efficiency
    - The Land Equivalent Ratio (LER) is used to measure the combined productivity of crops and electricity. Agrivoltaics often outperforms traditional single-use systems in terms of efficiency.
- Climate Resilience
    - Agrivoltaic systems can mitigate water stress by creating microclimates that reduce evaporation, moderate soil temperatures, and enhance water-use efficiency.
- Ecosystem Services
    - Positive impacts include biodiversity conservation, soil erosion prevention, and enhanced pollination. Vegetation beneath PV panels can reduce heat storage and improve the overall microclimate.
- Energy Access
    - APV systems can contribute to energy access in off-grid and underdeveloped regions, especially in sub-Saharan Africa, where irrigation needs are high.

Challenges and Trade-offs

- Shade Management
    - Crops under PV panels may experience reduced sunlight, which can impact yields unless they are shade-tolerant.
    - The orientation of PV panels can create uneven light distribution, affecting crop growth.
- Economic Considerations
    - Initial costs and the design of agrivoltaic systems must balance energy production with agricultural output to remain economically viable.

Case Studies and Applications

- Examples from countries like Germany, France, India, and Japan demonstrate the varying impacts of agrivoltaic systems on crop yields.
- Pilot projects in Benin illustrate how APV systems can support local agriculture while providing clean energy.

Future Perspectives

- Innovative Technologies
    - Advancements in PV panel designs, such as bifacial and semi-transparent panels,

allow better integration with agriculture.

- Global Potential
  - The document evaluates the global potential for agrivoltaics, emphasizing its scalability in areas with rainfed agriculture and limited energy infrastructure.

Agrivoltaics refers to the practice of using the same piece of land for both agricultural production and solar energy generation. This dual-use strategy optimizes land use, addresses the competing demands of agriculture and renewable energy, and can create synergistic benefits in certain environments.

Key Components of Agrivoltaics

1. System Design
Agrivoltaic systems are designed to balance light, water, and temperature requirements for both crops and photovoltaic (PV) panels. Key design considerations include:

- Panel Height: PV panels are elevated (typically 4–5 meters) to allow sunlight to reach crops and accommodate farming equipment.
- Panel Orientation and Spacing:
  - Panels are oriented at angles (e.g., 45° SW or SE) to maximize energy production while distributing light evenly for crops.
  - Spacing between rows of panels allows sufficient light to reach the plants below.
- Panel Types:
  - Semi-transparent panels or bifacial panels allow partial sunlight penetration.
  - Fixed or tracking panels optimize sunlight capture and adjust for crop needs.

2. Climatic and Crop Suitability
- Agrivoltaics works best in areas with:
  - High solar radiation.
  - Moderate temperatures (to avoid excessive heat stress on crops).
  - Limited water resources, where shade from panels can reduce evapotranspiration.
- Suitable crops include:
  - Shade-tolerant species: Leafy greens, herbs, and certain fruits.
  - Dryland crops: Wheat, barley, and grapes in semi-arid areas.
- Some crops, like rice and potatoes, show varying results depending on local conditions.

Benefits of Agrivoltaics

1. Increased Land Use Efficiency
- Land Equivalent Ratio (LER): A metric to evaluate productivity.
  - Formula: LER=Ycrop,APVYcrop,monoculture+Yelectricity,APVYelectricity,PVLER=Ycrop,monocultureYcrop,APV+Yelectricity,PVYelectricity,APV
  - LER > 1 indicates more productive use of land compared to single-use systems.

2. Microclimate Regulation
- Temperature Control: Panels provide shade, reducing heat stress on crops and soil.
- Water Savings: Shaded soil retains more moisture, reducing irrigation needs and mitigating water stress.

3. Energy Generation
- Solar panels provide clean energy that can power farm operations (e.g., irrigation pumps, processing units) or feed into the grid.
- Off-grid agrivoltaics offers energy access in remote areas, particularly in regions like sub-Saharan Africa.

4. Ecosystem Services
   - Reduces soil erosion by maintaining vegetation.
   - Enhances biodiversity by providing habitats for pollinators and other beneficial species.
   - Sequesters carbon by encouraging vegetation growth.
5. Economic Benefits
   - Farmers can diversify income by selling electricity.
   - Reduces energy costs for agricultural activities.

Challenges of Agrivoltaics

1. Shade Management
   - Excessive shading can reduce photosynthesis and crop yields, especially for light-demanding crops.
   - Panels must be carefully spaced and oriented to balance shading and sunlight availability.
2. Economic Viability
   - High initial installation costs may deter small-scale farmers.
   - Economic returns depend on electricity prices, crop yields, and subsidies for renewable energy.
3. Structural and Operational Challenges
   - Elevating panels and designing systems to accommodate farm machinery increases costs and complexity.
   - Maintenance must ensure both solar and agricultural components function optimally.
4. Socio-Political Factors
   - Competing land-use priorities and regulatory hurdles can limit adoption.
   - Acceptance by local communities depends on clear communication of benefits.

Examples of Agrivoltaics in Practice

Global Applications
- Germany: Studies show a small reduction in yield for crops like wheat and potatoes but significant increases in land-use efficiency.
- India: Agrivoltaics on grape farms demonstrated water stress mitigation and yield stability under high radiation.
- France: Crops like alfalfa have shown yield improvements under agrivoltaic conditions.
- Japan: Rice yield variations depend on shading levels and regional factors.

Field Projects
- Benin (Porto Novo & Savalou): On-field agrivoltaic installations for tomatoes, cabbages, and green beans are improving energy access and crop productivity in local communities.

Future of Agrivoltaics

Technological Advancements
- Tracking Panels: Adjust angles to optimize sunlight capture for both electricity and crops.
- Radiation-Splitting Panels: Direct specific wavelengths for electricity generation while letting photosynthetically active radiation (PAR) reach crops.
- Organic Solar Cells: Lighter and more adaptable panels integrated with agriculture.

Global Potential
- Agrivoltaics is particularly promising in areas with:
  - High energy needs and limited land (e.g., Europe).
  - Water-scarce regions where microclimate benefits are significant.
- Studies suggest agrivoltaics can contribute to closing the yield gap in rainfed agriculture by improving water and radiation management.

WATER ENERGY NEXUS

Hydrogen

- Achieving climate neutrality requires eliminating CO2.
- Hydrogen: it has many advantages, as for example versatile, clean, integrated with infrastructure, decentralized. And for these reasons it could be considered the fuel of the future to decarbonize hard-to-abate sectors.

this is not a energy source like light or wind, but it's a carrier of energy. We can look at the hydrogen rainbow: white is the natural hydrogen, black (produced from coal), and then up to green hydrogen.

- Hydrogen's applications: renewable energy sources like solar and wind are intermittent, hydrogen instead plays a crucial role in the energy mix by providing a reliable storage solution.

Its application can be:

- Industrial decarbonization.
- Energy and storage.
- Heavy transport.
- Heating and residential use.

- Future hydrogen: the idea is to convert existing hydrogen uses maybe to infrastructures etc… the idea is to expand the market. Up to 2050 hydrogen will be expanded to all the sectors, reaching the 500 Megatons.
- Green hydrogen: in 2050 electrolysers will account for 60% of total hydrogen production. Water electrolysis is the process whereby water is split into hydrogen and oxygen through the application of electrical energy.

water is required as an input for production and as a cooling medium for all types of hydrogen production. The energy transition is not only about reducing CO2 emissions but also requires assessing the potential negative impacts of emerging technologies.

total water demand for hydrogen is projected to have relatively minimal hydrological implications on a global scale compared to other sectors. Local and regional water constraints can limit the production and exportation capacity of electrolytic hydrogen. At the local level, the presence of electrolysers in areas affected by water scarcity can exacerbate the limitations in water availability due to competing demands for water.

graph of the green hydrogen water footprint: blue line= water withdrawal. A part of it it's water consumption (=part of water withdrawal that exits from the balance). 9 is the stechyometric water consumption and the rest is evaporating water. Water consumption is 23,6 for an alkaline process.

more than 35% of the global green and blue hydrogen capacity is located in highly water stressed regions.

the most of water consumption is through agriculture, which is more or less the 70%.

case of Spain: between all the European countries, Spain wants to expand its energy market in a more extended way. There are 88 green hydrogen plants in the territory. All the plants are operative at the maximum regime. Hydrogen consumption has a relative influence compared to other sectors. Water implications from green hydrogen production has not huge impacts.

All the plants are fully operative and at the maximum regime with the production stable along the year: so the same amount of hydrogen is produced in all the months of the year.

THEN sum up all the water consumption from these plants and I have compared them to the other water consumption on the other sectors. The consumption is the last bar and it is negligible respect to the to the other sector. But this is a specific case because the water consumption for agriculture is very, very high compared to the others.

So next, I evaluated the blue water scarcity on the basin scale. Water scarcity is the lack of sufficient available water resources to meet the demands of water use within a region.

HOW: I run a model. I think you already have seen that part in the labà physically based model that takes the flow direction and flow connection to find the water supply in each cell. As an input for the calculation, we have the water withdrawal from the different sectors for industrial, domestic and agriculture and the runoff that tell us the water availability and water supply. That's the way I calculated the blue water scarcity cell by cell at the basin scale,

RESULT 1: first scenario without considering the water consumption from hydrogen plants. So this is the current situation and we can see that in Spain we have severe condition of water scarcity mostly during spring/summer and in the centre & south. Only in the northern moderate or normal blue water condition but just for few months during the year.

POSITIVE RESULT 2: scenario from running the model with the application of water consumption of hydrogen production. No big differences from 1 à positive results because we can demonstrate that the H production doesn't have a repercussion of water scarcity level, so no impact.

- For example, here we have the month of April in the precondition and the post condition of hydrogen production. But if we go to the cases around Valencia where there are 4 plants. Here in the we pass from a condition of no water scarcity to a condition of severe water scarcity especially on the coastal area

So we can see that the impacts on the water scarcity are localized around the point of withdrawals. There is a relationship between blue water scarcity conditions in the month of April. So we have a limited influence on the water quality downstream anyways in some. Points like this one, this one, the degradation in water scarcity is very high - up to 160%.

CASE STUDY: ITALY

With its geographical location and extensive gas network of 32.700 km, Italy could serve as a «Infrastructural Bridge» between Europe and Africa in the green hydrogen transition.
Why this would serve as an infrastructure bridge? Because mainly the cost of producing green hydrogen from solar resources in African continent is lower than produced the same amount of hydrogen in Europe. This is mainly due to availability of solar resources.
But this is not the only reason. Also, the comparative costs are lower. Map of Hydrogen costs from solar PV and onshore wind systems.

So looking at the data in 2020, the content in the energy mix was very, very low, like 2% of the total energy mix. But following the next year mission pathway it will rise up to 13 or 14%.
METHOD: as before, it has been selected 37 projects on the basis with the production at the full regime of three gigawatts, that's around five 543 kilotons per year. So to analyze their present and future implications

- Baseline Scenario 0 (2030): hydrogen plants are fully operational at declared capacities.
- Scenario 1 (2030): hydrogen plants are fully operational at increased capacities to replace existing brown/grey hydrogen actual uses.
- Scenario 2 (2040): hydrogen plants are fully operational at increased capacities to replace 25% of energy uses in the transport sector, and implement phase 1 of a hydrogen-methane mix in the national gas network.
- Scenario 3 (2050): hydrogen plants are fully operational at increased capacities to replace 100% of energy uses in the transport sector, and implement phase 2 of a hydrogen-methane mix in the national gas network.

These scenarios were analyzed using different climate models. RCP 2.6. RCP 4.5. RCP 8.5.
RCP 4.5 has been used as a reference scenarios because it described well the condition of emissions togetjer with effort in decreasing emissions.

RESULTS with current climate:
Most of the plants are located in place suffering water scarcity conditions all the year, in all scenarios analysed

- Local Water scarcity: precise measure of water scarcity for each cell, indicating the specific values of water scarcity experienced in the point of water withdrawal
- Average Water scarcity: frequency of water scarcity, number of months that every single cell experience water scarcity (from 0 to 12).

In the summer, the water scarcity is at very, very high level and this is due to many factors.

- the increase in the average consumption, especially in the agriculture sector with irrigation and domestic uses.
- during summer we typically have less precipitation and higher temperatures à higher evapo-transpiration rates.

We can see for example from all these couple of rows that the marginal increase of water scarcity related to water consumption for green hydrogen production is very minimal and they cannot be sold observable

If 30% of the plants experience water scarcity for all the months, then water availability is not considered as a critical factor in the feasibility study.

- Conclusions:
  - Hydrogen will play a key role in the decarbonization of many sectors.
  - Water consumed for hydrogen will not have big impacts.
  - It is important to consider local water contexts.
  - Hydrogen production project in areas affected by water scarcity can be incentivized to use water-efficient cooling technologies.
  - In present and future fresh-water stressed coastal areas, utilizing seawater for hydrogen production and cooling processes should be incentivized.