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Research Article

Hydrogen Fueled UAV for Wildfire Fighting and Aerial Reconnaissance Coupled with Land Side Hydrogen Mobility

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Abstract

This paper introduces a new unmanned aerial vehicle system coupled with ground assets, all based on hydrogen fuel, for forest firefighting and rescue missions. A new firefighting index for fire suppression is defined. According to this index, the new system performs about 40% better in terms of heat absorption, range and suppressant to take off weight. The main advantage is that during operational flight the water released from the onboard hydrogen fuel cell supplements the on-board water tank, cooled by an adsorption cycle using the waste heat of the fuel cell. H'g=specific heat hemp nanoparticles also help the heat absorption capacity of water. Oxygen absorption for fuel cells is another attribute. Nearly green hydrogen is produced on the ground base using solar, wind and geothermal energy. The system comprises a mother UAV and several drones, all operating on nearly green hydrogen engines. The mother UAV design incorporates full dedication of AI-based computers for night-time operations and performs risky flight profiles successfully with high-G maneuvers. Mini UAV swarms, mini helicopters and hybrid ground control vehicles complement the fire suppression and rescue missions. Land-side operations are performed by hybrid hydrogen vehicles compromising hovering tracks connected to the air-side operations with a system of systems approach.

1. Introduction

Global warming keeps increasing primarily due to human-induced CO_2 emissions (Kabir et al., 2023). In 2024, global forest fires destroyed or damaged twelve million hectares of forests all over the globe. Consequently, forest fires seem to be one of the reasons why the goals of the Paris Agreement for decarbonization by 2050 will not be achieved on time. Early detection is much more important than fire suppression and limitation. This mission needs satellite imaging but may more effectively be achieved by swarms of UAVs. The latest data on forest fires confirms that they are becoming more widespread, burning at least twice as much tree cover today as they did two decades ago (MacCarthy et al., 2024). Using the University of Maryland data covering the 2001 to 2023 period, the area of forest fires increased by about 5.4% per year. Forest fires are responsible for about six million more hectares of tree cover loss per year than in 2001 (Afshari, 2018). Global warming is the primary cause of forest fires. On the other hand, each acre of forest fire releases about 170-ton equivalent CO_2, comprising methane and nitrous oxide. Trees absorb CO_2 in their body and when burnt, they release them to the environment. On average, twenty-five kg of CO_2 is absorbed by a single mature tree each year (Stancil, 2015). One of the major drivers behind increasing fire activity is dry and high temperatures due to global warming. Each thousand Gton of CO_2 released into the atmosphere causes an increase in the global temperature by 0.45 °C. At the same time, mature forest trees absorb kg of CO_2 annually. This potential is destroyed by each burnt tree. New tree saplings need at least thirty years to attain the same decarbonization potential. Therefore, a seemingly unstoppable vicious cycle between forest fires and global warming exists. This vicious cycle is further accelerated by the fact that warmer air can hold more water vapor. Water vapor is itself a greenhouse gas, which further accelerates the greenhouse effect (EPA, 2024). In this respect, simply relying on water for fire suppression and cooling must be questioned because water vaporizes and mixes with the atmosphere. Therefore, some other means of fire suppression must be sought. Another pressing subject of decision-making is whether ground or air mobility is better for forest fire suppression. When economic concerns are prioritized, land suppression is generally preferred and air suppression is recommended only for the initial stages of fire until the ground assets reach the area (Bushfire CRC & AFAC, 2009). This reasoning is not true because airside assets are effective in all stages of forest fire, provided that they work together with the ground assets.

2. Theory

Recently, UAVs have become familiar with forest fires (Castro et al., 2018). Yet their performance characteristics and effectiveness at many sizes and types are not completely known yet. In this study, a wildfire fighting, rescue and reconnaissance UAV system, which is coupled with landside systems comprising hybrid hovercraft-tracked vehicles, renewable hydrogen production facilities and a control center has been designed. The main objective is to coordinate every step and enhance firefighting with minimum water vapor release. All systems run on nearly green hydrogen. This process is called nearly green because even if onsite solar and wind energy are used, there always occur exergy destructions, which directly translates to nearly avoidable (ΔCO_2) emission responsibilities. Fig. 1 shows this condition for a solar PV, which generates electric power at a modest efficiency, η_{IPV} and rejects the rest of the solar insolation, I_n over the PV cells. This rejection results in local heat island and exergy destruction, E_{Xdes}. The solar PV panel partially replaces demand from thermal power plants, but this replacement is usually less than or equal to the emission responsibility of the solar PV Panel (ΔCO_2).

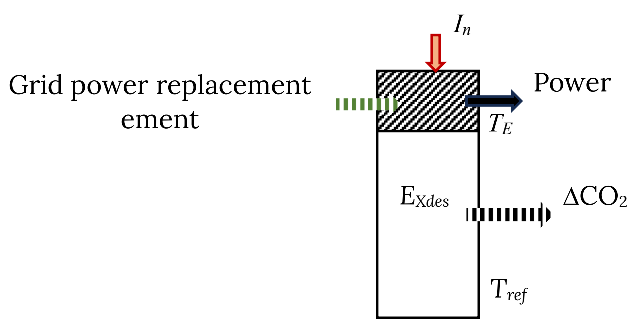

Fig. 1. A solar PV Panel and its ΔCO_2 Emission Responsibility Due to Exergy Destruction, E_{Xdes}

In Eq. 1, the proportionality constant (k) symbolizes the need for offsetting the exergy destruction, E_{Xdes}, by someone, somewhere and by some other means, possibly by using fossil fuels with their exergy destructions, like a boiler.

$$\Delta CO_2 = k \times E_{Xdes} \quad (1)$$

If the major exergy destruction occurs upstream of the useful work obtained, the multiplier (k) is 2.1 kg CO_2/kW-h_{ex}. Otherwise, it is 1.1 kg CO_2/kW-h_{ex}. Another expression for ΔCO_2 is given in Eq. 2, in terms of the Rational Exergy Management Model (REMM) efficiency (ψ_R), which is a measure of exergy imbalance (destruction) between supply and demand. The lower the exergy destruction (better exergy match) is, the higher the (ψ_R) and thus lower the (ΔCO_2). If is above 0.70, the system is 'nearly' green, because the ideal condition (ψ_R = 1) is not possible due to irreversibility.

$$\Delta CO_2 = k \times E_{Xsup} \times (1 - \psi_R) \quad (2)$$

$$\psi_R = 1 - \frac{E_{Xdes}}{E_{Xsup}} \quad (3)$$

Based on commercial solar PV plants in the grid, the formula to determine the limiting ΔCO_2 emission responsibility for one kg of hydrogen gas produced under standardized conditions is given in Eq. 2. The non-zero ΔCO_2 condition shows that completely green hydrogen is not possible, even if all embodiments are ignored. In other words, the definition of nearly-green hydrogen will be practical.

$$\Delta CO_2 \le k \times \left[\left(1 - \frac{T_{ref}}{T_E}\right) \times \frac{(1-\eta_{IPV})}{\eta_{IT}}\right] \times B > 0 \quad (4)$$

The term (B) is the electrical energy required for electrolysis to generate one kg of hydrogen. According to Antweiler (2020), it is about 40 kW-h_E/kg H_2. With Fig. 1 and Fig. 2., ΔCO_2 can be calculated. T_{ref} is the environment reference temperature, T_E is the temperature of the PV panel frame that loses heat to the environment, η_{IT} represents the transmission losses of the grid. η_{IPV} is the First-Law efficiency of the solar PV panel for electric power generation.

ΔCO_2 = 1.1×[(1-283 K/335 K)×(1-0.2) /0.90] ×40 kW-h_E /kg H_2= 6.07 kg ΔCO_2/kg H_2

From the above calculation, the (η_{IT}) term drops if the PV plant is on site of hydrogen production on the ground side.

Fig. 3. shows the exergy flow bar of hydrogen generation by electrolysis. It is assumed that the waste heat of electrolysis replaces a boiler if that heat is captured and utilized in useful applications like adsorption cooling.

$$\sum_{elect} CO_2 = \Delta CO_{2elect-1} + \Delta CO_{2elect-2} - [CO_2 + \Delta CO]_{boiler} \quad (5)$$

Based on hydrogen energy produced on the land side, the UAV fleet comprises a mother ship (airside command center), firefighting UAV swarms and helicopters, all running on green hydrogen. UAV propulsion and power supply are compared with 1-grid electric UAV, 2-nearly-green grid electric UAV and 3- composite power system UAV, which is presented in this paper.

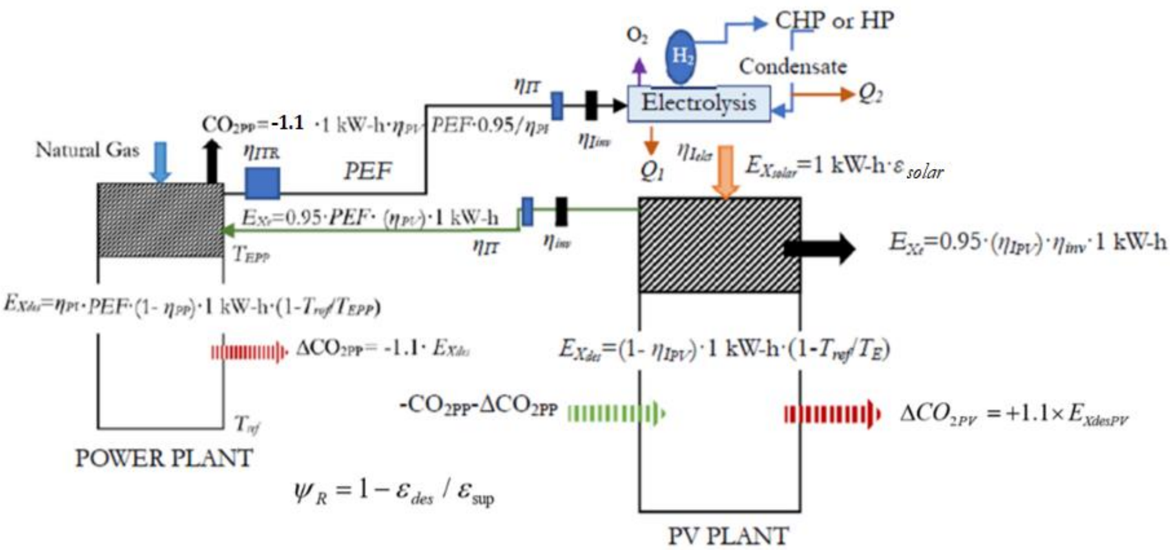

Fig. 2. Emissions Background of Grid-Connected Solar PV Plant and Hydrogen Power Plant

This research has developed a new fire suppression index, *FSI*, for aerial firefighting systems. It involves the range, maximum fire land area that may be covered in one mission, suppressant fill weight to the takeoff weight of the aerial vehicle. The proposed system has an estimated FSI of 60 kW/m of fire suppression capacity. This is about 40% better than other comparable aerial firefighting systems.

$$\text{Fire Supression Index FSI}=\frac{\text{Heat Absorption Rate [kW/m}^3\text{]}}{\left(\frac{1}{\text{Fire Area Covered [m}^2\text{]}}\cdot\frac{\text{Take off Weight}}{\text{Suppressant Weight}}\right)}=60\text{ kW/m} \tag{6}$$

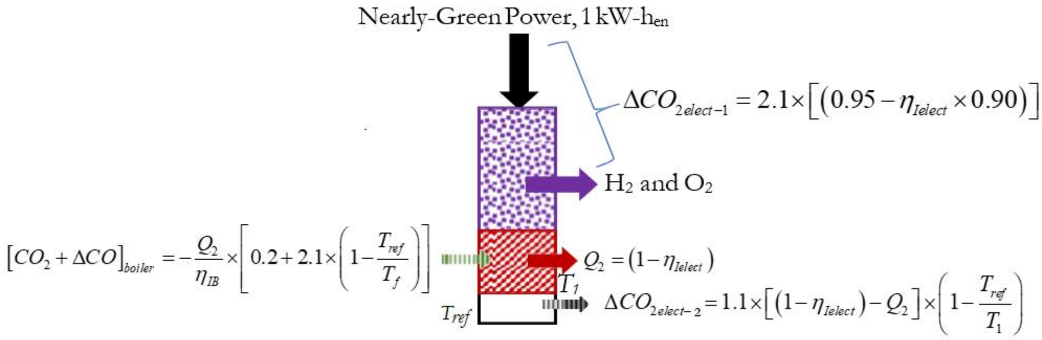

Fig. 3. Exergy Flow Bar and Emissions for Electrolysis

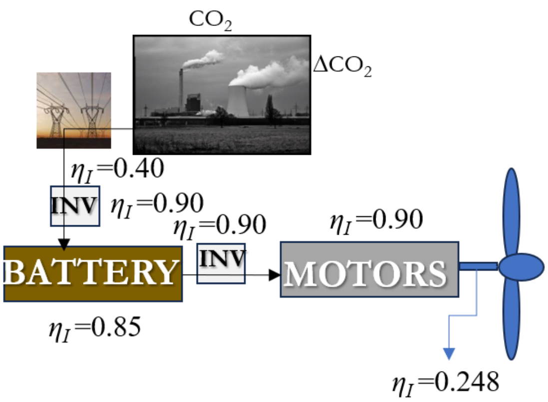

Fig. 4. Fossil Fuel-Grid Electric Driven UAV

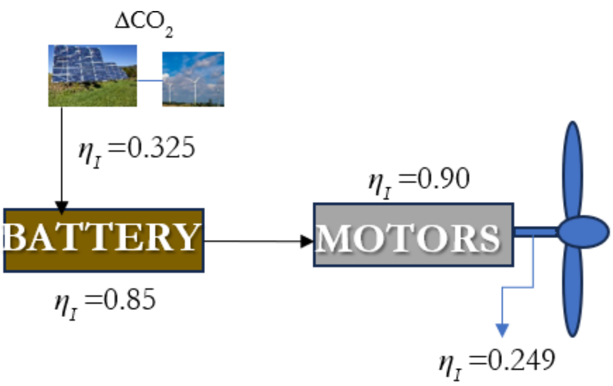

Fig. 5. Nearly Green Grid Electricity UAV

Power plants emit CO_2 as well as ΔCO_2 because they reject the downstream heat (Like in the case of solar PV panels) through the cooling towers, instead of utilizing this thermal power in district energy systems. Depletion of scarce water resources and the greenhouse effect of water vapor are other issues. The overall First Law fuel efficiency from plant to propeller is only 0.248 in this example. In Fig. 5, Power is supplied to the batteries from renewables in the form of DC power. Onboard batteries deliver DC power to DC motors, this time. The First Law efficiency is not much better, almost the same with Case 1.

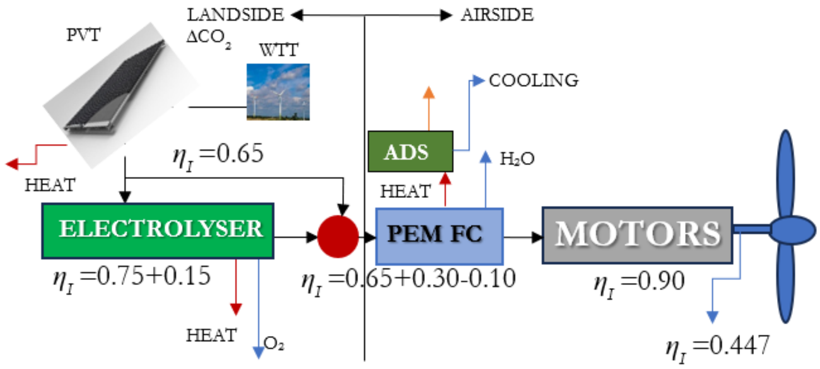

Fig. 6. Alternative 3: Composite Hydrogen Power System UAV

Fig. 6 shows the new hydrogen UAV concept. It consists of two sections. The first section is on the land side where renewable energy systems produce hydrogen gas by water electrolysis and it is stored. The heat and oxygen by-products of this process are used (or stored) for useful purposes on the land side complex. Hydrogen gas in cassette type of tanks is loaded onto the UAV. On the air side (UAV), PEM fuel cells generate power, which drives electric motors. Reject heat of the PEM fuel cell is converted to cold through an onboard adsorption cooling machine to chill the fire extinguishing water tank. The H_20 byproduct supplements the water tank. Thus, the reloading frequency of water from the ground side is reduced giving a better performance. The overall First Law efficiency is higher than the other cases (0.447) and the (ψ_R) value of 0.85 exceeds the limit for green applications but is not equal to one. Case 3 is the best environment-friendly and the best-performing alternative on the drawing board. The remaining task is to optimize the subsystems.

Table 1. Alternative Power Supply Systems to the UAV. kg CO_2 per kW-h electrical energy consumed

Alternative	Overall η_I	ψ_R	CO_2^*	ΔCO_2	Total Emissions
1	0.248	0.30	1.3	0.89	2.19
2	0.249	0.45	-	0.40	0.40
3	0.447	0.85	-	0.20	0.20

* Based on a natural-gas combined cycle power plant. Primary Energy Factor (PEF): 2.5.

Table 1 compares the three alternatives in terms of the First Law, the REMM efficiency, ψ_R and CO_2 emission responsibility. See Fig. 4, Fig. 5 and Fig. 6. In Fig. 2, a fossil fuel power plant supplies AC power through the grid. It is inverted to DC through inverters (INV), stored in onboard batteries and then generally re-converted to AC to drive the propellers with electric motors. This table shows that an electric aerial vehicle is responsible for environmental pollution if the power comes from the grid. This responsibility is about six times more than alternative 3 and three times more than alternative 2. It must also be noted that ΔCO_2 even in alternative 3 is greater than zero because of inevitable, irreversible exergy destructions. Following these preliminary results, a compound power supply with green hydrogen UAVs has been designed (Fig. 7).

3. Method

Fig. 7 is a longitudinal cutaway illustration of the mother UAV. This UAV has multiple functions, like air side control of UAV swarms, maintaining the coordination with the land side operations, coordinating with mobile ground control and fire suppression by multiple means, including hydrogen bombing.

The hydrogen UAV receives hydrogen cassettes at the ground station, which generates hydrogen from renewables. All forms of energy are utilized on the land side for hydrogen production. On the UAV, hydrogen is utilized in the PEM fuel cell and electric power and heat are generated, while oxygen in the air is locally consumed (depleting against fire). Water generated in the process is added to the water tank that sprays the water on the fire target. Additives with high specific heat, like hemp, are added in the form of nanoparticles. The water supply from the PEM FC improves the range for firefighting. On the ground, hydrogen-driven mobile units with tracks and air cushions are designed for rescue and onsite monitoring and fire control purposes. See Fig. 8.

This vehicle has deployable skirts such that it can morph into a hovercraft to travel fast over smoother surfaces like plains, lakes, or the sea to harness water, or by folding the skirts up, it may morph into a tracked vehicle over rough terrain and forest land.

One of the important tasks is its early fire detection, personnel transport back and forth, rescue and ambulance missions on the land side. This vehicle can partially generate its own hydrogen supply by raising the propellers mounted on telescopic columns at its stationary position by using the hydro foiling and driving propellers as wind turbines.

Solar PVT systems complement the hydrogen production and heat demand of the vehicle for different purposes. It also absorbs oxygen in the fire area (depletion effect), stores water and delivers it back to the ground station. A compound wildfire detection, fighting, rescue and reconnaissance missions have been designed, based on nearly green hydrogen produced on the land side where the main ground control is built in the potential wildfire areas.

The main control may be decentralized with mobile hydrogen vehicles that can resist wildfires and can be used for close rescue missions. When they are parked in a safe area for near site controls and management, they can also generate green hydrogen. The air side is composed of a mother ship UAV and a swarm of UAVs.

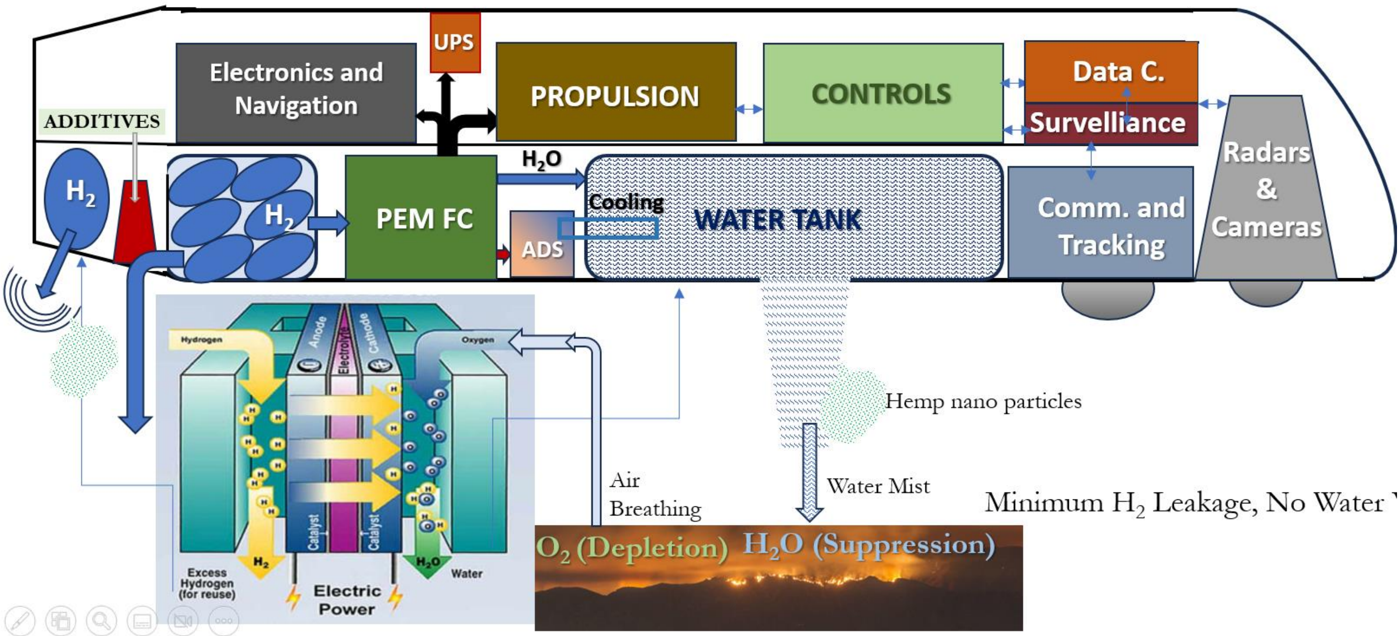

Fig. 7. Air Side of the System: Hydrogen Mothership UAV

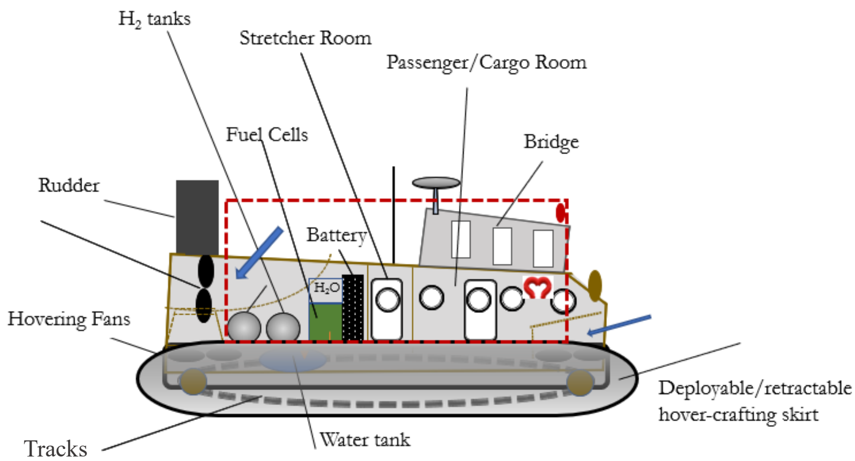

Fig. 8. Ground Side of the System: Hybrid Hydrogen, All Terrain, Amphibious Ground Control, Multitasking Vehicle

4. Results and Discussion

The backbone of the system is the predictive wildfire spread model (Fig. 9), which feeds information simultaneously to the ground control center and the mother UAV on the air side (Kilkis et al., 2021).

This information is dynamically processed and commands are relayed both to ground hydrogen vehicles (Fig. 8) and the swarm UAVs. The Mother ship also functions as the primary aerial fire suppressant (Fig. 7). The concept drawing of the swarm UAV is shown in the upper inset of Fig. 10. These complete the coordination of multiple assets both on the ground side and air side.

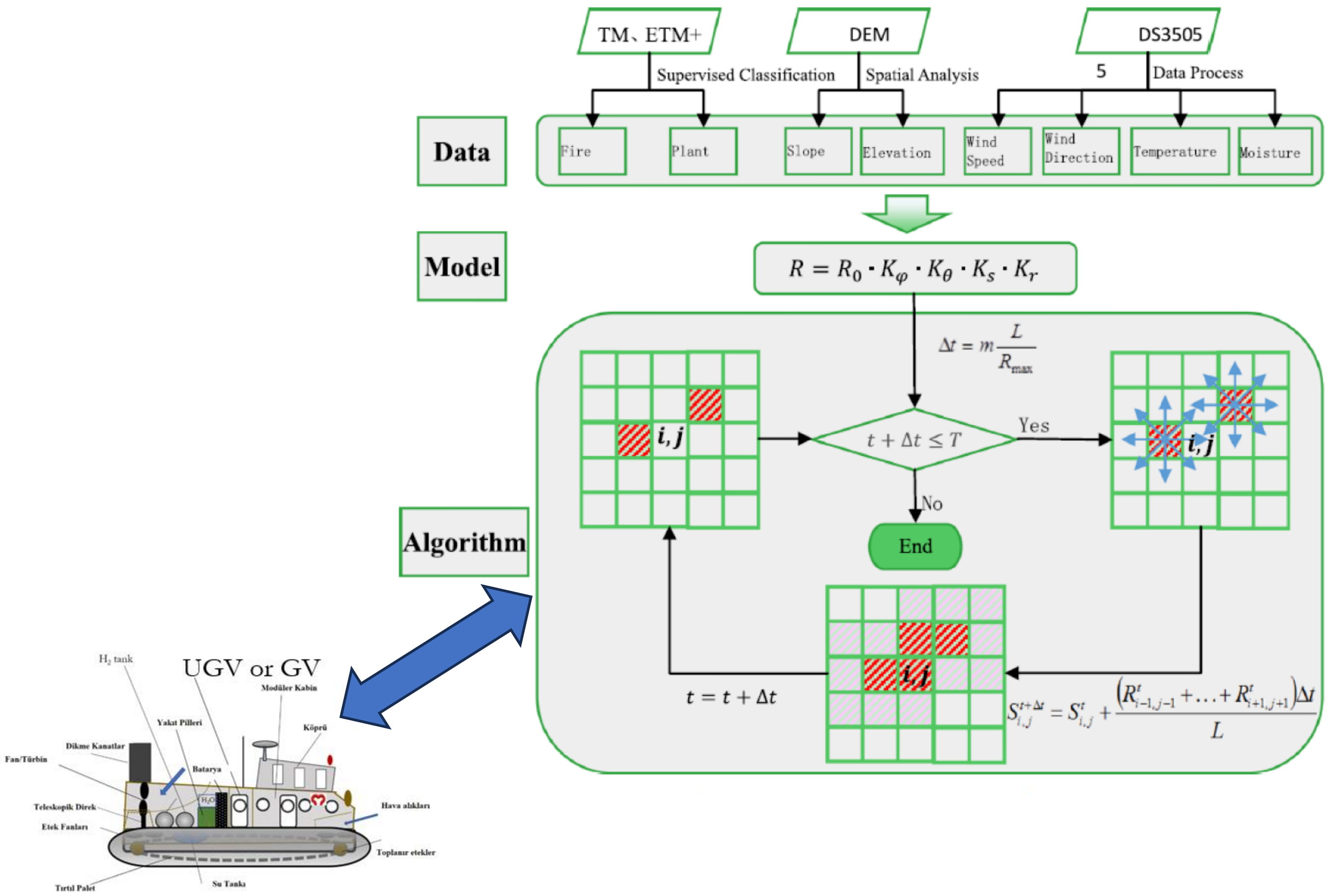

Fig. 9. Overview of Wildfire Spread Model. Mother UAV and Ground Control (Kilkis, 2019; Kilkis et al., 2021; Prakasha et al., 2021)

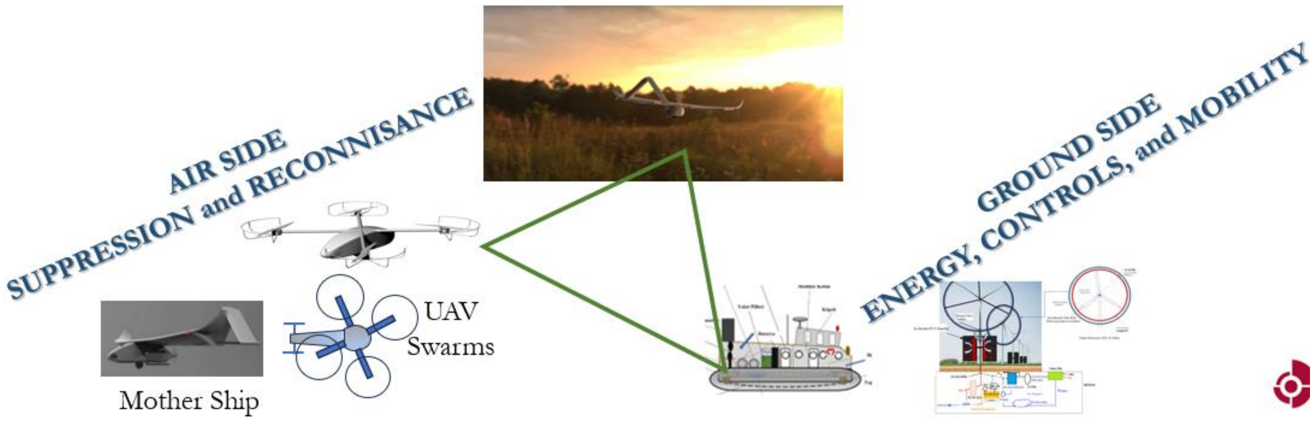

Fig. 10. Compound Firefighting and Rescue Mission Triangle: Coordinated Effort of Multiple Assets

Fig. 10 graphically shows these assets, including novel wind turbines and next-generation solar PVT systems. Usually, global warming-induced forest fires occur in warm and hot climates, which are ideal locations for PVT systems following assets and missions. The following items comprise the primary advantages and functions of these assets:

- Hydrogen UAVs, when fueled by renewables on site, are more energy and exergy-efficient.
- They have longer range and less reloading periods.
- Hydrogen combustion is cleaner than fuel cells but noisier. Therefore, this study replaces hydrogen motors with onboard fuel cells.
- Distributed electric propulsion (DEP) is quieter at take-off and landing but at the cruising flight, it does not help when rescue missions and sonic detection needs most. Therefore, this design relies on double propellers.
- Propeller shrouds are included to reduce noise. Noise is important for landside search and rescue missions.
- How much composites? (Fire susceptibility). This study optimized the use of composites in terms of lightweight versus fire risk (Kilkis et al., 2019).
- Hydrogen on board has multiple functions:
  - Propulsion
  - Fire suppression (with additives still under research)
  - Cooling of suppressant water
  - Acoustic surveillance for rescue. Propellers are at the back, sensors and sophisticated electronics are in the front.
  - Water supply (Extended range, less loading time)
  - Thermal energy is available for ancillaries on board
  - Aerial bombing (last resort)

5. Conclusions

In conclusion, a hybrid, hydrogen-based forest fire fighting and rescue mission has been conceptualized and designed, which is an environment-friendly high-performing integrated system with AI-supported control algorithms. It is expected that this design will contribute to decreasing the damaging effects and monitoring covering all phases starting with the early warning stage to the fire suppression stages. Furthermore, it may give a clue to break the vicious cycle between global warming and forest fires. This system provides minimum hydrogen leakage and no water vapor release. The future work should include detailed design and simulations prior to field tests, targeting an FSI of 45.

Abbreviations and Symbols

Latin Symbols

B : Electrolysis electric power demand, $kW\text{-}h_E/kg\ H_2$

CO_2 : Direct emission, kg/h or $kg/kW\text{-}h_{en}$

ΔCO_2 : Nearly avoidable CO_2 emission responsibility of a system or process, $kg\ CO_2/kW\text{-}h_{ex}$

E_X : Exergy, $kW\text{-}h_{ex}$

E_{Xdes} : Destroyed exergy, $kW\text{-}h_{ex}$

E_{Xsup} : Supplied exergy, $kW\text{-}h_{ex}$

FSI : Fire Supression Index, kW/m

I_n : Solar insolation, kW/m^2

k : Unit ΔCO_2 emission factor, $kg\ CO_2/kW\text{-}h_{EX}$

PEF : Primary energy factor

Q : Thermal output, $kW\text{-}h_{en}$

T_E : Exit temperature after useful work output, K (See Fig. 1)

T_{ref} : Environment reference temperature, K

Greek Symbols

ε : Unit exergy (According to the Carnot Cycle), $kW\text{-}h_{ex}/kW\text{-}h_{en}$

η_I : First Law efficiency

η_{IT} : Grid transmission efficiency

η_{IT} : PV efficiency

η_{IT} : Inverter efficiency

η_{IPP} : Power plant efficiency

ψ_R : REMM Efficiency

Acronyms

ADS : Adsorption Cooling Machine

AI : Artificial Intelligence

CHP : Combined heat and power

DEP : Distributed Electric Propulsion

E, *elect* : Electric (subscript)

EPA : Environmental Protection Agency

FC : Fuel cell

HP : Heat pump

INV : Inverter

PEM : Proton exchange membrane

PV : Solar Photovoltaic Panel

PVT : Solar Photovoltaic-thermal panel

REMM : Rational Exergy Management Model

UAV : Unmanned Aerial Vehicle

WT : Wind Turbine

Subscripts

B, *boiler* : Boiler

des : Destruction (Exergy)

elect : Electric

en : Energy

ex : Exergy

inv : Inverter

pp : Power Plant

ref : Reference (Temperature)

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