Young Economist of the Year 2021

Glenstal Abbey School
2nd year

Student Name:

Hugo Phelan

Is Space Exploration a Sustainable Enterprise? - Economically, Socially and Environmentally.

"Somewhere, something incredible is waiting to be known." – Carl Sagan

Personal Profile

My name is Hugo Phelan and I am in second year in Glenstal Abbey School. I decided to do this project since from a very young age, I have always had an extraordinary interest in Space and Space Exploration. As a child I read a lot, and at some stage I got a book by British astronaut Tim Peake, and that is when I remember first being really interested about space. This has led over the past few years to me becoming more and more interested in space exploration, and I am aiming to become involved in the aerospace engineering field when I am older.

UN Sustainable Development Goal

This project links in with Goal 9 , which is Industry, Innovation and Infrastructure. My project deals with aspects of all of these. It deals with industry in regards to the new companies springing up in the space sector. It deals with innovation in regards to the new tech developed for space flight that is then used here on earth and it deals with infrastructure in regards to the infrastructure that satellites provide to us on planet earth

Line of Enquiry

For the purpose of my research study, I am enquiring about the impact of Space Exploration on the Economy; because I want to ascertain firstly, if continuing to venture into space is sustainable from an Economic, Social and Environmental perspective; and secondly, how governments and politicians should plan for Investments in Space Programmes going forward (with a particular focus on Ireland's involvement in this area)

The aims of my project are:

1. Economic Sustainability: I will look at Ireland's investment in ESA, the European Space Agency, and see what dividends that investment pays, in addition to looking at the US/NASA and their investment in private spaceflight to see what benefits they reap from such investment.

2. Social Sustainability: I will look at the benefits of space from a social perspective, reviewing the inventions and innovations that were created for spaceflight, that now benefit society as a whole, together with the satellites in space that we use today, and the purpose of same, and the scientific discoveries made on the ISS that benefit humankind.

3. Environmental Sustainability: I will look at the sustainability of spaceflight, and the impact it has on the environment.

Research Study

This part is divided into three research elements. They are Economic Sustainability, Social Sustainability and Environmental Sustainability. They will explore the sustainability of spaceflight from each of the aforementioned angles.

Economic Sustainability

This element focuses on the economic sustainability of spaceflight. It will examine the investment the Irish Government makes in ESA, and the dividends that it pays. It will also examine NASA and the USA, and look at their investments in private space companies, to see if ESA and Europe would benefit from similar investments (or is ESA already investing, albeit at a smaller scale)

Firstly, Ireland's investment in ESA. During my research I found that between 2016 and 2020, Ireland contributed €97.8 million to ESA[(Page 14)] . On average, this means Ireland contributed €19.56 million per year. ESA's budget is about €5 billion[(ESA)] per annum, so Ireland contributes about 0.39% of ESA's budget.
Knowing how much Ireland contributes to ESA per year, led me to enquire as to how much of that money flows back into Ireland's economy. I understand that "*ESA operates on the basis of geographical return, i.e. it invests in each Member State, through industrial contracts for space programmes, an amount more or less equivalent to each country's contribution*"[3].
This should mean that Ireland's space companies should get at around €19/20 million per year in ESA contracts. While I couldn't find figures for this, I found that according to an Enterprise Ireland report: (4, Page 12/13)

1) Commercial sales by companies in Ireland directly resulting from ESA support expanded from €43m in 2013 to over €75m in 2015 and was projected to grow to €133m by 2020,
2) Companies in Ireland involved in ESA contracts had a combined turnover of €274m in 2013 and this was projected to increase to over €0.5B by 2020, and
3) Total employment in companies benefiting from ESA in Ireland was expected to more than double from 2,000 in 2014 to over 4,500 in 2020. ESA related employment is generally of high skill and high salary, providing long-term employment.

In my opinion, this indicates that

1) Ireland's space economy will keep growing, especially with ESA investing,assuming that the projected upward trend continues and
2) The fact that it should keep growing will lead to the companies expanding, and employing more people, and as the report says, "*ESA related employment is generally of high skill and high salary, providing long-term employment*". I believe that as long as there is an ESA to provide these contracts, this particular sector of the economy will continue to expand.

Indeed, the Irish space economy has gained quite a few companies working with ESA between 2010 and 2018, from34 in 2010[Page 11], to a total of 67 [(Page 12)] in 2018 (note: this includes research organisations). The global space economy has been growing faster than the global economy in recent years. The space economy has been growing at a rate of 6.7% per annum between 2005 and 2017, compared to 3.5% for the global economy[(Page 9)]. Furthermore, the commercial space industry worldwide is expected to be a trillion dollar industry by the end of this decade[(Page 9)].

An example of an Irish company working in the Irish space industry is Réaltra Space Systems Engineering (a division of Realtime Technologies Ltd.). In 2019, they got €1m to develop a video stream (Independent Video Kit) from ESA's upcoming rocket, the Ariane 6.

Now to take a look at NASA. NASA is awarding many contracts to commercial companies to develop space systems for Low Earth Orbit (LEO). Part of NASA's rationale is that if NASA can get these companies to develop rockets, spacecraft and space stations, then NASA can be the ones to first start paying them for their services, but then other companies/agencies will also buy their services - thereby developing an economy independent of NASA in Earth orbit.
The advantages of this is firstly that it is expanding the economy, and secondly, NASA does not have to worry about running their own rockets (they can leave that to SpaceX and Boeing) and NASA can focus on exploring the frontiers of space. A third advantage is that NASA no longer has to pay Russia to launch their astronauts on the Soyuz spacecraft, which was very expensive ($82m -> $54m per seat)

An example of NASA encouraging third party development is SpaceX's Crew/Cargo Dragon spacecraft. This spacecraft was developed to bring NASA astronauts and cargo to the international space station, as part of the Commercial Crew and Cargo Resupply Services (CRS) contracts (these are billion dollar contracts) but now in a few months the first all-private space mission will launch. It is called Inspiration-4, and without NASA providing contracts, it is doubtful that it would exist.

There are many other companies involved in the developing space industry , such as Virgin Galactic, which is developing short tourist trips to space, and Virgin Orbit, which is providing a small satellite launch system. An advantage with the Virgin Orbit satellites is that they are launched from a plane, thereby using less fuel, and the satellites can go into any degree of orbit. The system is also mobile and could launch from literally anywhere, which because they are expected to be more expensive than alternatives, will mean they have a unique selling point to their service.

In my opinion, Europe would benefit from having a larger space industry like the US. However, there are some problems associated with this. One such problem is that Europe's spaceport, used by the Arianespace organisation to launch the Ariane 5 (and Russian Soyuz), is in French Guiana [(Wiki)], in South America. While it is far away,

which could be a problem for manufacturers in Europe (it would be harder to get the rockets to the spaceport, because they would have to go by sea), the advantage is that because it is closer to the equator, the Earth's rotation gives it more speed starting out, and therefore the rocket doesn't have to be as powerful to reach orbital velocity.
To compare this with NASA, the spaceport in French Guiana is 5 degrees from the equator, and every orbit is possible because of its location on the east coast of South America (the spent rocket stages drop harmlessly in the sea).
However, the USA has two main launch sites. They have Kennedy Space Center (KSC)/Cape Canaveral Space Force Station [(Wiki)], in Florida, as well as Vandenberg Air Force Station[(Wiki)(Wiki)], in California. KSC is at 28 degrees North, and has access to most orbits, with the exception of a polar orbit, which requires a complex trajectory to avoid dropping spent boosters on Cuba. Vandenberg Space Force Station is at 34 degrees North, and has access to high inclination orbits, including a polar orbit. The different orbits have different benefits. For example, many earth observing missions, as well as SpaceX's Starlink and the ISS are in Low Earth Orbit, around 700km above the earth. Other communications satellites are in Geostationary orbit, where they stay above the same point on earth. GPS satellites are in a semi-synchronous orbit. A Sun-Synchronous Orbit is also popular for earth observation, and is also popular for spy satellites under the guise of “earth observation”.

Another problem to ESA investing more, is that ESA's budget is €5 billion a year, while in 2020, NASA's budget was $22.6 billion ($22.9 billion today = €19 billion) [(ESA)(NASA)]. That means that ESA has about a quarter of NASA's funding. ESA therefore has less money to spend on investments. However, I believe because of ESA's partnership with NASA to build the Orion spacecraft service module, ESA will not be left behind as NASA returns humans to the moon.

If ESA had more funding, it could have a more active role in international spaceflight. ESA could invest more in the ISS program, and get more ESA crew time on the station. ESA could also create their own plans, such as creating a crew capsule, or unveiling a plan for a new space station.

Social Sustainability

This element will focus on how sustainable space is from a social perspective and how it benefits society on earth. This means looking at the “spinoff” technologies from spaceflight exploration and the dividends paid by exploring space, as well as the services provided by infrastructure in space such as satellites, and the scientific discoveries made on the ISS that benefit us all on Earth.

Firstly, the “spinoff” technologies [(NASA)]. These are technologies that were developed out of items originally designed for spaceflight. There are many examples of these. I will look at the technologies that will make the biggest difference for us on Earth. Some of these technologies include:

More efficient solar panels - solar panels are one of several options to power spacecraft and space stations. By making them more and more efficient, they can be used in space over less safe power supplies (such as Radioisotope Thermal Generators, which use heat from plutonium to produce electricity and are mainly used on new robotic missions such as the Mars 2020 Perseverance rover), as well as helping make our energy grid renewable on Earth. They make our grid renewable by being a source of energy that we can’t use up, unlike coal or gas. Other examples of renewable energy are wind turbines and hydroelectric power stations.
However, super efficient solar panels are useless without batteries. Why? Because the sun doesn't shine the whole time. The ISS charges its batteries in sunlight with its solar panels, then when it is away from the sun, it uses the power in the batteries to power the station. Batteries like these are not only used in space, they are also used in commercial applications like portable electronics, as well as electric cars. They are also used to store electricity from when renewables produce more than the current demand, so the electricity can be used when renewable energy is not producing enough to meet demand.

NASA has also developed a water purification system for the ISS. The ISS reuses up to 90% of its water. It extracts and purifies the water from the air, washing, sweat and even urine. This technology is used in developing countries to provide clean drinking water.

NASA has also developed a very fire resistant polymer fabric, that is now used in firefighters clothes.

Furthermore, some of the lightweight low power sensors developed for observing other galaxies, and other phenomena in the universe, are also used in phones, because of their low power needs, and high quality.

There are many dividends paid from exploring space. Some of them benefit the economy, and some of them benefit society. Space agencies exploring space need many different things, and to provide them, there are many different contractors. Back in the Apollo era in America, there were many companies supplying NASA with different components. These included: Boeing, Chrysler, General Electric, IBM, McDonnell Douglas, Rocketdyne and Rockwell [(NAFL)]. All these companies employed many people, and both directly and indirectly provided tens if not hundreds of thousands of jobs to people.

Secondly, there are the services that satellites provide to us on Earth. These include precise navigation using GPS or Galileo (the EU’s version of GPS), weather monitoring and satellite internet. Weather monitoring satellites have provided better

warning of storms and hurricanes, perhaps saving many lives as earlier warning is given for these huge storms.
Internet satellites come in two main categories. There are large satellites out in geostationary orbit (this orbit stays above the same part of the Earth the whole time), and small satellites in Low Earth Orbit (LEO). The large satellites have very high bandwidth(i.e., a lot of data can go through one satellite) but because they are relatively far away from Earth, they have high latency (latency is how fast the signal between your computer and the host server of the website is). High latency is fine for most applications, like downloading and web browsing. However, it is not so good for video meetings, stock market trading and online gaming. It is not good for the three aforementioned applications, because those applications require the signal to go very quickly to every computer connected. The higher the latency, the laggier your video meeting or online game will be. It is important for stock trading because the big companies on the stock markets rely on exploiting tiny variations in stock price. The faster they get the signal with the price data, the more money they can make.
This is where low latency satellite constellations in LEO come in. Currently, the only one operational is SpaceX's Starlink, which is currently in Beta testing with consumers. When all the satellites are deployed, it may even have less latency than the undersea cable that is currently used by stock exchanges like the ones in New York and London. This could mean companies working on these stock exchanges will use it, for the reasons stated above.
However, low latency satellites have disadvantages too. One disadvantage is that it (the low latency satellite constellation) will end up having in the region of 10,000 satellites in just one internet constellation, which will have significant consequences for Earth based telescope observatories. This will affect them because the satellites will reflect light from the sun, which will be picked up by the telescopes as a point of light. This will distort a telescope's observation.
There are also other concerns and benefits to low latency satellites. One benefit that I think could happen is that the satellite dishes that you pick up the signal with could be leaked, which would mean people in countries with restricted internet access (eg. China, Iran, North Korea) could access Starlink, if they could build their own receivers. A disadvantage may be that if Starlink is fully complete before another competitor (like Amazon) is operational, they could have a monopoly over this space internet, and therefore could control it, especially if it becomes significantly cheaper than Earth based alternatives. This could be disadvantageous because a third party could pay them to take a website off their internet, and if they force Earth based alternatives out of business, they could just take all their competitors' websites offline. This is why I think that a satellite constellation would have to be carefully controlled, but it could be a source of good too, as charities could provide these receivers to remote/poor communities in developing countries, to help connect them to the wider world.

Lastly in this section, I will talk about the scientific discoveries made in space that benefit humankind. There are many different discoveries that have been made, from

potential for treating osteoporosis sufferers, to the origins of life on Earth, and potential new cancer drugs.
In space, astronauts' bones deteriorate because they are living in microgravity, an environment where gravity is absent, and they therefore have barely any work to do, so the body doesn't bother maintaining them. However, astronauts combat this by doing 2 hours of hard exercise each day, as well as having carefully calculated nutrient intake. This may lead to a breakthrough in treating osteoporosis, which afflicts millions of people worldwide (Independent).
Experiments on the ISS have also exposed bacteria to the extreme environment of space (e.g., vacuum, very cold/very hot temperatures), and have found that some bacteria survive. This begs the question; do bacteria hitch a ride to other planets on our spacecraft, and are Earth bacteria living on mars, brought by one of our rovers or landers? It also raises the question of if our bacteria can survive in space, did life originate somewhere else in the solar system, and was it then brought here by an asteroid or comet (Independent).
Research on the ISS has helped develop new microcapsules, which are tiny balloons that can be delivered to the site of a cancer tumour using a special needle. The research on the ISS found new ways of using fluid mechanics, which was then replicated on Earth. This could be a revolutionary system for curing more advanced cancers that could save many lives (ScienceFocus).

Environmental Sustainability

This section will focus on the environmental sustainability of spaceflight. It will focus on the rocket fuel used, and will examine different types of rockets, to see if some fuels are worse than others, and if the rockets using less environmentally friendly fuels are actually worth it.

There are many different fuels used in rockets. They can be split into two categories, solid and liquid. All rocket fuels need a fuel source, and an oxidiser. In a solid rocket, these are combined in a hard substance. In a liquid fuelled engine, these are mixed together in the combustion chamber, at high temperatures and pressures.

I will first look at the environmental impact of rocket fuel. The fuels I intend looking at are RP-1 + LOX (Keralox), Hydrogen + LOX (Hydrolox), Methane + LOX (Methalox), Solid Rocket Fuel and Hypergolic Fuels (LOX means Liquid OXygen).

For launches with Keralox, the main byproducts are Carbon Dioxide, Water Vapour, Carbon Monoxide and Soot. Most of the Carbon Monoxide will bond to become Carbon Dioxide. There are also Nitrogen oxides and sulfuric compounds emitted, in small amounts. These are basically the same as emissions from a combustion engine in a car, but just in much larger amounts.

The end result is that the main byproducts that affect the atmosphere the most are the Carbon Dioxide and Water Vapour, which are both greenhouse gases. The soot, Carbon Monoxide and other trace gases come from the fact that hydrocarbons (what RP-1 is made of) are not all the same. Greenhouse gases trap heat in the atmosphere, leading to the phenomenon known as global warming.

For rockets using Hydrolox, the main byproduct is Water Vapour. It is probably the cleanest fuel, however hydrogen is not very dense, which means it takes more space in the rocket. This means the rocket has to be bigger for the same power. It does have quite a punch, as it is the fuel being used in NASA's upcoming SLS rocket. It was also the liquid fuel used in the space shuttles main engines. Hydrolox is the most efficient liquid fuel.

For rockets using Methalox, the main byproducts are Carbon Dioxide and Water Vapour. Because Methane is such a powerful greenhouse gas, it is actually better off in its constituent parts of 1 CO_2 and 2 H_2O, when burnt with oxygen. It is not actually used in any rockets yet, but it is used in SpaceX's Starship prototypes, and will be used in their Starship rocket. One of the reasons Methalox is used in Starship is because it can be manufactured using materials available on Mars, and SpaceX plan to send Starship to Mars.

Next up are Hypergolic fuels. These are not a nice bunch, with most of them being highly toxic and carcinogenic. They are stable for long periods of time, making them useful for ICBM (Inter - Continental Ballistic Missiles). Not many rockets use them nowadays. They mainly emit Carbon Dioxide, Water Vapour, Soot and Sufuric compounds.

Finally, there are Solid Rocket Boosters. These are very powerful. They gave the space shuttle millions of pounds of thrust. However, they are probably the worst of the lot in terms of emissions. They mainly emit aluminum oxide, soot, CO_2, hydrogen chloride, nitrogen oxides and hydrogen. These are used on the Atlas V and the Ariane 5, and will also be used on NASA's upcoming SLS rocket. An advantage of these is they can provide a huge amount of thrust.

I will look at some of the more common rockets used today, and the fuels they use. The rockets I am looking at are the Atlas V, Delta IV Heavy, Falcon 9/Heavy, Electron, Ariane 5, Vega and Soyuz.
(I don't have the time to do a more in-depth exhaust:payload comparison)

Rocket	Fuel	Main Emissions
Delta IV Heavy US ULA	Hydrolox	Water Vapour

(Wiki)		
Falcon Heavy US SpaceX (Wiki)	Keralox	Carbon Dioxide, Water Vapour, Soot
Falcon 9 US SpaceX (Wiki)	Keralox	Carbon Dioxide, Water Vapour, Soot
Soyuz (2.1b) Russia TsSKB-Progress, Chemical Automatics Design and Starsem (Wiki)	Keralox	Carbon Dioxide, Water Vapour, Soot
Electron US/New Zealand RocketLab (Wiki)	Keralox	Carbon Dioxide, Water Vapour, Soot
Ariane 5 (ECA) Europe Arianespace (Wiki)	Hydrolox + SRB	Water Vapour, Aluminum Oxide, Soot, Carbon Dioxide, Hydrogen Chloride, Nitrogen Oxides and Hydrogen.
Atlas V US ULA (Wiki)	Keralox + SRB Hydrolox	Carbon Dioxide, Water Vapour, Aluminum Oxide, Soot, Hydrogen Chloride, Nitrogen Oxides and Hydrogen.
Vega Europe Arianespace, ESA, ISA (Italy) (Wiki)	SRB Hypergolic (UDMH + N_2O_4)	Aluminum Oxide, Soot, Carbon Dioxide, Hydrogen Chloride, Nitrogen Oxides, Hydrogen, Water Vapour and Sufuric Compounds

The above table details the rocket, the fuels that rocket uses and the gases it emits to the atmosphere. It is in the order of best exhaust to the worst.
The best is ULA's Delta IV Heavy, which runs on Hydrolox and only releases H_2O. The next rockets are the Falcon 9, Falcon Heavy, Soyuz and Electron. These all use Keralox and emit Carbon Dioxide, Water Vapour and Soot.
Next up is the Ariane 5, operated by ESA, which uses SRBs and Hydrolox. It emits Water Vapour, Aluminum Oxide, Soot, Carbon Dioxide, Hydrogen Chloride, Nitrogen Oxides and Hydrogen. After this is the Atlas V (Second last place). This emits Aluminum Oxide, Soot, Carbon Dioxide, Hydrogen Chloride, Nitrogen Oxides, Hydrogen, Water Vapour and Sufuric Compounds.
Finally, in last place is ESA's Vega. It emits Aluminum Oxide, Soot, Carbon Dioxide, Hydrogen Chloride, Nitrogen Oxides, Hydrogen, Water Vapour and Sufuric Compounds.

ROCKET EMISSION TOTALS [METRIC TONNES]

	FUEL	CO_2	WATER VAPOR	SOOT	NOx	INORGANIC CHLORINE	ALUMINA	SULFUR CONTAINING COMPOUNDS
TITAN II	HYPERGOLIC	36	16	0.2	0.3	0	0	0.3
SOYUZ FG	RP-1 + HYPERGOLIC	243	64	13	0.4	0	0	~0
ATLAS V N22	SRB + RP-1 + HYDROGEN	259	111	2.1	0.8	21.4	30	~0
FALCON 9	RP-1	425	152	30	1	0	0	~0
DELTA IV HEAVY	HYDROGEN	~0	632	0	0.5	0	0	0
SPACE SHUTTLE	SRB + HYDROGEN	443	976	4.2	7	250	350	~0
SLS	SRB + HYDROGEN	538	1346	5.1	8.5	302.5	423.5	~0
STARSHIP + SUPER HEAVY	METHANE	2683	2199	0	1.7	0	0	0

EVERYDAY ASTRONAUT

This table (Tables) shows the fuels, and then the Metric Tonnes of different gases produced. The rockets are the Titan II (Hypergolic), Soyuz (Keralox + Hypergolic), Atlas V (SRB + Keralox + Hydrolox), Falcon 9 (Keralox), Delta IV Heavy (Hydrolox), Space Shuttle (SRB + Hydrolox), SLS (SRB + Hydrolox) and Starship (Methalox).
The table below shows the same rockets, their payload to orbit, and then the ratio of gas emitted to the payload to orbit.

EMISSIONS TO PAYLOAD MASS RATIO [METRIC TONNES]

	PAYLOAD TO LEO	CO_2:PAYLOAD	H_2O:PAYLOAD	ODS:PAYLOAD
TITAN II	3.5	10	4	~0
SOYUZ FG	7	35	9	~0
ATLAS V N22	13	20	9	4
FALCON 9 (REUSED)	15.5	27	10	~0
FALCON 9 (EXPENDABLE)	22.8	19	7	~0
DELTA IV HEAVY	29	0	22	~0
SPACE SHUTTLE	28	16	35	21.7
SLS	95	6	14	7.7
STARSHIP + SUPER HEAVY	100	27	22	~0

It is also important to appreciate that the higher up in the atmosphere the emissions are the longer they stick around, and the more heating they cause. Also worth mentioning, is that there is a huge amount of carbon emitted as the rockets are made, so companies such as SpaceX and RocketLab are already better as they are reusing or trying to reuse most of the rocket, as it also saves them money.

Findings

Economic Sustainability

In the area regarding the economic sustainability of space exploration, I found that Ireland contributes about €19 million to ESA per year, which is 0.39% of ESA's total budget of €5 billion. I also found that "*ESA operates on the basis of geographical return, i.e. it invests in each Member State, through industrial contracts for space programmes, an amount more or less equivalent to each country's contribution"* This should mean that they invest around €20 million into Ireland by giving Irish companies contracts for ESA programs. According to an Enterprise Ireland report, commercial sales from Irish companies directly resulting from ESA support was over €75m in 2015, and was projected to be €133m by 2020. The turnover of those companies was projected to be €0.5B by 2020, and it was projected to be 4,500 jobs related to ESA in Ireland by 2020. I also found that there are 67 companies and research institutions working with ESA in Ireland, and that the global space economy has been growing at twice the rate (6.7%) of the global economy (3.5%), and is expected to be a trillion dollar industry by the end of this decade.

This means if Ireland keeps investing like it already is, it will continue to reap the rewards.

I then looked at NASA, and I found that what they are doing is they are investing in companies to develop a commercial economy in Low Earth Orbit. They have many contracts such as Commercial Resupply Services (CRS) and Commercial Crew to deliver supplies and astronauts to the ISS, and Human Landing Services (HLS) and Commercial Lunar Payload Services (CLPS) to land humans and cargo on the moon as a part of the Artemis Program. These contracts have already led to non-government funded commercial activity in space, with the Inspiration-4, the first all civilian mission to space, set to launch on a Crew Dragon spacecraft on a Falcon 9 rocket - all made by SpaceX, and paid for by private individuals (one person funded it - there was a competition for the other three seats).

I then said that Europe would benefit financially from having a larger space industry like this. However, there would be problems. One problem is that ESA's spaceport is in South America (French Guiana), which means for a European company to get their rocket there, it costs much more money, and has a greater chance of something going wrong. In America, it is easier to transport the rockets to the launch site, as there is the existing infrastructure to take them there, or they are made very close to the launch site.
I then found another problem with ESA investing in private companies. It is that ESA's budget is a quarter of NASA's (€5B to €19B), which means they can't give the billion dollar contracts that NASA gives

Social Sustainability

In this section, I was looking at the sustainability of spaceflight from a social perspective. I looked at the spinoff technologies developed for spaceflight, the dividends paid by exploring space, the infrastructure that satellites provide and the scientific discoveries that benefit humans on Earth.

When I looked at the spinoff technologies I found that among many, many things, more efficient solar panels, and better batteries were developed, as well as water purification systems. These technologies are now being used on Earth to make our electricity grid renewable, and to provide clean water in developing countries.

When I looked at the dividends paid, I found that the main one was the fact that space employs a lot of people. For example, during the Apollo program, and still today, there are many companies contracted by NASA and other space agencies to build parts for rockets and spacecraft. All of these companies directly and indirectly employ large numbers of people.

Next, I found that the satellites in space have several functions. Some are for internet/communication, others are for weather monitoring. I found that the internet satellites can provide internet to poor/rural communities, speed up the stock exchanges and provide low latency online gaming. However, I also think that these satellites can ruin telescope readings, and if one company was to have a monopoly on this high speed low latency internet, and especially if it were cheaper than earthbound alternatives, then measures would have to be taken to prevent the internet being controlled by one entity. However, by the fact that the satellites are passing over the entire earth, this means that countries with restricted internet perhaps would no longer be able to disconnect their citizens from the world.

I also found out that there is valuable scientific research being done on the ISS. Among many experiments, some are finding possible cures for osteoporosis, others are providing data for theories concerning the origin of life, and most importantly, researchers are making microcapsules that may be able to be used in cancer treatments. Making these capsules may not have been possible without the experiments on the ISS.

Environmental Sustainability

In this section, I was looking at the environmental impact of rockets, and I found that there are many types of rocket fuel, with varying degrees of worseness for the environment.

I found that there were two main types of rocket fuel, solid and liquid. Solids are definitely worse for the environment, however, they pack a huge punch when launching rockets.
I found that the main rocket fuels are Keralox (RP-1 + LOX), Hydrolox (Hydrogen + LOX), Methalox (Methane + LOX), Hypergolic Fuels and Solid Rocket Fuel.
In the order of worst to best, they are Solid Rocket Fuels (*produces aluminum oxide, soot, CO_2, hydrogen chloride, nitrogen oxides and hydrogen*), Hypergolic Fuels (*produces Carbon Dioxide, Water Vapour, Soot and Sufuric compounds*). Next is Keralox (produces Carbon Dioxide, Water Vapour, Carbon Monoxide and Soot), Methalox (produces CO_2 and H_2O) and finally Hydrolox (produces H_2O). The reason I ranked Methalox and Hyrolox as the cleanest is because while water vapour is a potent greenhouse gas, it would go out of the atmosphere and into the water cycle, which is much quicker than the CO_2 in the carbon cycle.
I also found that some rockets are better than others, with the best one I looked at being the Delta IV Heavy (USA), and the worst being Vega (Europe).
I also found out that the potency of the greenhouse gas depends on its height in the atmosphere (higher is worse), and that a rocket's reusability affects how much carbon is released.

Conclusions

In this section, I will present what I set out to find, and then I will conclude with what I found.

Economic Sustainability

In this section, I set out to take a look at

1.) Ireland’s investment in ESA, the European Space Agency, and see what dividends that investment pays, in addition to
2.) looking at the US/NASA and their investment in private spaceflight to see what benefits they reap from such investment.

Firstly, I can conclude that Ireland's investment in ESA (~ €20m/year) is worth it, as commercial sales for companies supported by ESA was projected to be €133m by 2020, the turnover of these companies was expected to be €0.5b by 2020, and around 4,500 Irish people are employed in jobs relating to ESA. I believe that this will only increase and keep growing into the future.

Secondly, I can conclude that NASA’s investment in private spaceflight is worth it, because NASA no longer has to pay Russia for expensive flights to the ISS ($82m per seat to $54m per seat). NASA was able to do this by having contracts for US aerospace companies to develop their own spacecraft to bring people to the space station. One reason why they are doing this is to save money like I said above, but another reason is if NASA can begin to set up an economy that consists of US companies operating in space, that is essentially a previously unknown sector of the market that they have just opened up. These companies will pay taxes to the US government, so it will provide a new source of income for the government. I can conclude from this that NASA is reaping the benefits of this investment already, with SpaceX already launching crew missions to the ISS (Crew-2 is up next), and they are also launching the first completely privately funded crewed mission to space (Inspiration-4).

Social Sustainability

In this section, I set out to look at

1.) the “spinoff” technologies from spaceflight exploration,
2.) the dividends paid by exploring space as well as
3.) the services provided by infrastructure in space such as satellites, and
4.) the scientific discoveries made on the ISS that benefit us all on Earth

Firstly, I can conclude that there are many spinoff technologies from spaceflight. Some of them are more widely applicable than others. However, all of them are benefiting Earth in one form or another. I believe that these technologies are an advantage from spaceflight, and that they are part of making spaceflight sustainable by giving back to the Earth.

Secondly, I can conclude that there are indeed positive social dividends paid from exploring space. The main one that I can think of is the fact that there are a lot of contractors employed in the industry, therefore they create many jobs for skilled workers that will likely have long term employment.

Thirdly, I can conclude that the infrastructure provided by satellites is sustainable and worth it, because it not only provides internet services, they also play a role in weather forecasting, and in particular forecasting the paths of big storms. However, there are dangers with satellite internet and one company having a monopoly, so I believe it will need to be regulated to work properly.

Finally I can conclude that the scientific research on the ISS is 100% worth it and sustainable. I say this because there are not only experiments that are creating new medicines and even a possible cancer cure, they are also finding out facts about the cosmos, and the origins of life in our solar system.

<u>Environmental Sustainability</u>

In this section, I set out to take a look at

1.) the environmental sustainability of spaceflight.
2.) the rocket fuel used, and
3.) the different types of rockets and rocket fuel, to see if some fuels are worse than others, and if the rockets with worse fuels are actually worth it.

Firstly, I conclude that spaceflight is relatively environmentally sustainable, because there are a pretty small number of flights, however, each flight can release many tons of gases into the atmosphere.

Secondly, I can conclude that the best fuel is Hydrolox, next up is Methalox, then Keralox, Hypergolic fuels and Solid Rocket Fuels. My rationale for choosing Hydrolox as the best even though water vapour is a fairly potent greenhouse gas, is that it would evaporate out of the atmosphere quickly as it is a part of the water cycle. I do not believe the same can be said of the CO_2 produced by Keralox, Hypergolic fuels and Solid Rocket Fuels.

Thirdly, I conclude that there are many different types of rockets. Some are cleaner than others. For example, the Delta IV Heavy, operated by ULA in the US, was the rocket I found had the cleanest exhaust, with it being practically all water vapour. The worst rocket was the Vega, operated by ESA and Arianespace. It has three stages of

SRBs, and then an optional 4th stage of hypergolic fuels. The next best rockets are the kerlox ones, the Falcon 9, Falcon Heavy, Soyuz and Electron. Next is ESA's Ariane 5, which is a very reliable rocket (SRBs and Hydrolox). Second last is ULA's Atlas V which is also a very reliable rocket (SRBS, Keralox and Hydrolox).
I also want to say that the environmental sustainability of the rocket does not have much correlation with its price or payload, as the Delta IV Heavy can cost around $350 million dollars, and launches very infrequently. The Falcon 9 is quite cheap, and launches more often, but it does not run on a particularly clean fuel.

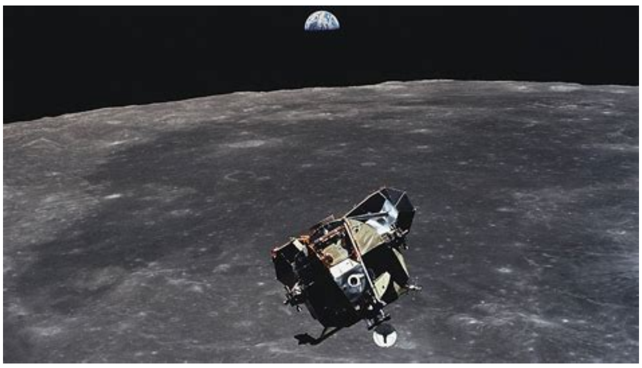
I would also like to note that the exhaust's potency as a greenhouse gas depends on the altitude it is at, with the higher it is meaning it is more potent as it will not recycle out of the atmosphere as quickly. On top of that, I would like to mention ion engines, which are engines that take a heavy, inert atom such as zenon, ionize it (give it an electrical charge), and then use magnets to push it out the back of the spacecraft. This would be environmentally friendly, because xenon is inert, but it produces too low thrust to be used on earth. They are instead used in space. However, a version of these that can take xenon from the higher atmosphere has been developed, and could be used to keep a satellite in a low orbit as the thrust from this could counteract the atmospheric drag experienced at such low altitude. This could enable better earth observation, and more accurate tracking of climate change.

Final Conclusion

When I started this project, I set out to answer the question "***Is Space Exploration a Sustainable Enterprise? - Economically, Socially and Environmentally.***"
I believe I can unequivocally conclude that yes, spaceflight is a sustainable enterprise. I am only unsure of this fact with some of the rocket fuels used, and the fact that not all rockets are reused like the Falcon 9. I am also unsure about satellite internet constellations, as I fear it could be too easy for a company to get a monopoly. This may point to the need for extra research in this area.

I also stated my project was going "to discover how Governments should plan for Investments in Space Programmes going forward (with a particular focus on Ireland's involvement in this area)"
I believe that I have answered this question, as I have laid out what NASA are doing, and the fact that they are already reaping the rewards. I would also say that for Europe to do this, we would need to at least double, if not quadruple our funding to match NASA's. More realistically, I think we should be investing in colleges for STEM, especially aerospace, as I believe only one college in Ireland offers a degree in Aerospace Engineering (UL). In my opinion we need to expand our colleges more anyway, to have more STEM courses, and to lower the costs of college to encourage more people to go to college and get advanced degrees to join a technologically advanced workforce.

Another, more human, part of space travel is that it enables us to look down on our own planet. It not only can help keep an eye on more rogue regimes that may pose a danger, it can let us examine ourselves from a distant perspective. I have read that many astronauts have said to put the world leaders up in orbit, and let them gaze down on our blue marble, and realise that all their borders which they care so much about, are non-existent, and can't be seen. From space, we are all humans.



This picture was taken by Apollo XI Command Module Pilot (CMP) Michael Collins. This image contains every single achievement, argument, war, squabble, country, and even every person, alive or dead, except one. The photographer, CMP Collins

Thank you for reading my project, I hope you found it interesting

I want to say thank you to my teacher, Miss O’Sullivan, for helping me with this project

References

https://enterprise.gov.ie/en/Publications/Publication-files/National-Space-Strategy-for-Enterprise-2019-2025.pdf

http://www.esa.int/About_Us/Corporate_news/ESA_facts

https://en.wikipedia.org/wiki/Guiana_Space_Centre

https://en.wikipedia.org/wiki/Kennedy_Space_Center

https://en.wikipedia.org/wiki/Vandenberg_Air_Force_Base

https://en.wikipedia.org/wiki/Vandenberg_Space_Launch_Complex_6

https://www.planetary.org/space-policy/nasas-fy-2020-budget

https://www.nasa.gov/directorates/spacetech/new_interactive_website_homeandcity

https://www.nalfl.com/?page_id=2561&cpage=1

https://www.independent.co.uk/news/science/five-key-scientific-findings-15-years-international-space-station-a6796211.html

https://www.sciencefocus.com/space/five-things-the-iss-has-done-for-us/

https://en.wikipedia.org/wiki/Delta_IV_Heavy

https://en.wikipedia.org/wiki/Falcon_Heavy

https://en.wikipedia.org/wiki/Falcon_9_Full_Thrust

https://en.wikipedia.org/wiki/Soyuz-2#Soyuz-2.1b

https://en.wikipedia.org/wiki/Rocket_Lab_Electron

https://en.wikipedia.org/wiki/Ariane_5

https://en.wikipedia.org/wiki/Atlas_V

https://en.wikipedia.org/wiki/Vega_(rocket)

https://everydayastronaut.com/rocket-pollution/ - https://docs.google.com/spreadsheets/d/1h_o_yWq8LmU2AyJN3BwZOF8wy3OZVdadM_5c1JMznZE/edit#gid=0

http://www.esa.int/Space_in_Member_States/Ireland

https://www.un.org/sustainabledevelopment/infrastructure-industrialization/

https://www.enterprise-ireland.com/en/research-innovation/companies/access-eu-research-innovation-reports/european-space-agency-.html

https://www.enterprise-ireland.com/en/Research-Innovation/Companies/Access-EU-Research-Innovation-reports/ESA-End-of-Year-Report-2019.pdf

https://www.enterprise-ireland.com/en/Research-Innovation/Companies/Access-EU-Research-Innovation-reports/Space-Industry-Directory/

https://www.enterprise-ireland.com/en/Research-Innovation/Companies/Access-EU-Research-Innovation-reports/Space-Industry-Directory/Realtra.html

https://enterprise.gov.ie/en/Publications/Publication-files/National-Space-Strategy-for-Enterprise-2019-2025.pdf

https://esamultimedia.esa.int/docs/corporate/This_is_ESA_EN_LR.pdf

https://en.wikipedia.org/wiki/Comparison_of_orbital_launch_systems

https://www.universetoday.com/119599/adventures-in-satspotting-why-are-different-orbits-needed-for-satellites/