Huhtiniemi PV – 150 kilowatt Photovoltaic Power Plant

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Executive summary

In this report, the profitability of the Lappeenranta Huhtiniemi sports center rooftop photovoltaic power plant investment is appraised. Switching from grid electricity to photovoltaic electricity reduces greenhouse gas emissions, and it has an effect on other environmental impacts too. These effects are assessed and reported.

The study is made on the case where 1000 m^2 polycrystalline photovoltaic solar panels are assembled on the roof of a sports center. The nominal power of the photovoltaic system is 153.8 kW (153.8 kWp or “kilowatt-peak”). In Finland, 80% of nominal power can be achieved at best. During the lifetime of the photovoltaic power plant, the system is estimated to generate in total 2.9 GWh of electricity.

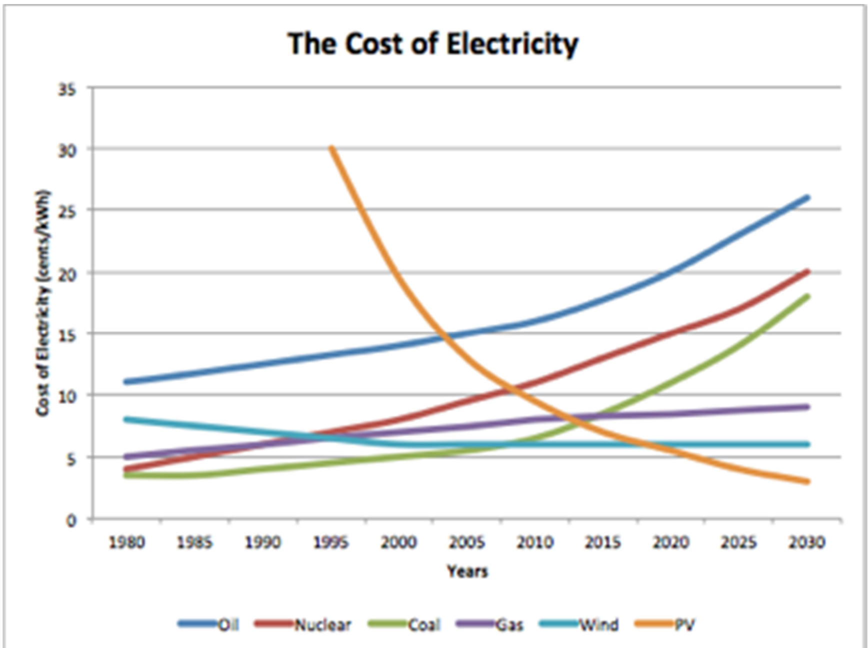
Compared to the grid electricity (Lappeenrannan Energia) and most other electricity options, the environmental impacts of photovoltaic electricity are superior. The capital investment appraisal shows that the photovoltaic investment is profitable, even without tax credit and investment subsidy.

Dr. Kimmo Klemola has wide experience on various issues such as the use of natural resources, energy and transportations solutions, environmental impacts of emissions, industrial processes and life-cycle and environmental appraisals. Kimmo Klemola is a former chemical engineering professor.

Contents

Introduction

In recent years, we have witnessed escalated costs of new nuclear power plants and falling costs of photovoltaic systems and wind power. Solar and wind electricity are today cheaper than nuclear electricity. The reason is not only the generous subsidies and tax credits to renewable energies, since fossil fuels and nuclear energy have benefitted from subsidies for decades and still receive a lot more subsidies than renewable energies.



The cost of photovoltaic and wind electricity generation has declined consistently over the past 25 years[1].

When fossil-fuel generated electricity or nuclear electricity is replaced with electricity produced by solar photovoltaic cells, there are many positive environmental impacts, which are assessed in this study:

- Global warming potential (GWP)
- Depletion potential of the stratospheric ozone layer (ODP)

[1] Kiss Zoltan, Trends in the cost of energy, www.seekingalpha.com, 05.04.2013.

- Acidification potential (AP)
- Formation potential of tropospheric ozone photochemical oxidants (POCP)
- Eutrophication potential (EP)
- Air toxicity (AT)
- Water toxicity (WT)
- Hazardous waste production (HWP)
- Particulate emissions
- SO_2 emissions
- NO_x emissions
- Methane emissions
- N_2O emissions
- Non-methane hydrocarbon emissions
- CO emissions
- High-level nuclear waste (HLW)
- Medium- and low-level nuclear waste (MLW+LLW)
- Petroleum consumption
- Energy depletion

Certain important environmental impacts are not quantified in this report. For example, the effect on water tables depends on geographic location. The effect on the loss of biodiversity is also difficult to appraise. For example, increased energy use of biomass decreases fossil fuel combustion, which in the long term mitigates climate change and also loss of biodiversity. However, increased energy use of biomass may lead to deforestation, monocultures and other land-use changes, directly or indirectly, thus causing the loss of biodiversity.

The leading standards for life cycle assessment (LCA) are ISO 14040 and ISO 14044.[2] These international standards focus mainly on the process of performing an LCA.

The cradle-to-gate environmental impacts of Huhtiniemi sports center rooftop photovoltaic system were assessed using a proprietary in-house life-cycle-analysis tool. Similar life-cycle assessments were done for other electricity generation options: Lappeenrannan Energia Oy

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[2] Life Cycle-Based Sustainability — Standards & Guidelines, PRé North America Inc., 2012.

electricity mix (grid electricity in Lappeenranta), Finland electricity mix, world electricity mix, natural gas electricity in Finland (98% is CHP), coal electricity in Finland (51% is CHP), nuclear and wind. In allocating combined heat and power production impacts to electricity, the benefit sharing method was used[3].

In economic feasibility study, the photovoltaic electricity price was compared with the grid electricity price (Lappeenrannan Energia Oy). The following methods were used: the payback period method, the equivalent annuity method and the net present value method.

Goal and scope

The purpose of this inventory report is to characterize resource inputs and environmental impacts and releases associated with the photovoltaic electricity generation. In its lifetime, the 153.8 kWp photovoltaic system is estimated to generate in total 2,895,000 kWh of electricity.

Process description and system boundaries

The environmental impacts of a photovoltaic system are caused by:

- Extracting and refining raw materials
- Manufacturing of solar panels, inverters, support assemblies and cables
- Transportation
- Assembly
- Maintenance

Photovoltaic panels consist of the photovoltaic cells (typically made of polycrystalline silicon), the top surface cover tempered solar glass and the aluminium frames. The photovoltaic system also includes the inverter, the support system and electric cables. The transportation distance is assumed to be 1000 km (made in Germany, truck cargo). The embodied materials of the photovoltaic system per m^2 solar panel are:

- 8.10 kg tempered solar glass

[3] Benefit-sharing method, Motiva, http://www.motiva.fi/files/6820/Kuvaus_hyodynjako-menetelmasta.pdf (in Finnish).

- 2.70 kg aluminium
- 5.40 kg stainless steel (inverter and support system)
- 0.19 kg copper (solar cables)
- 0.02 kg polyethylene (solar cables)

The electronic grade polycrystalline silicon wafers are processed into solar cells and the cells are combined into monocrystalline modules. Due to wafer shaping 1.11 m^2 of wafer is needed per 1 m^2 module.

As quartz is a common substance on earth and easy to mine, energy use in raw material extraction is assumed to be small and it is neglected from calculations. Metallurgical grade silicon is produced from quartz in a large furnace. Coal is commonly used for reduction. Metallurgical grade silicon is converted to trichlorosilane by the Siemens method. Trichlorosilane reacts with hydrogen in a large electric furnace producing electronic grade polycrystalline silicon. This is molten in a big pot, a crucible, in which a monocrystalline seed is planted. A monocrystal ingot grows around the seed and is slowly pulled out and cooled with a Czochralski process. 28% material losses are assumed. The ingot is sliced into wafers with a multi-wire saw. Further 10% losses are assumed in wafer shaping.[4]

The data used in the life-cycle inventory is from the first and second decade of the 21st century.

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[4] Wafer production, for photovoltaic cells, ESA-DBP, CPM LCA Database, 2006.

Table. The electricity generation mix (%) of different electricity generation options of this study (CHP = share of combined heat and power generation).

Electricity source	Coal Finland		Natural gas Finland		Nuclear		World electricity		Finland electricity		Lappeenranta electricity		Wind		Solar PV	
	Share %	**CHP %**	**Share %**	**CHP %**	**Share %**	**CHP %**	**Share %**	**CHP %**	**Share %**	**CHP %**	**Share %**	**CHP %**	**Share %**	**CHP %**	**Share %**	**CHP %**
Crude oil	0.00	0.00	0.00	0.00	0.00	0.00	5.80	13.24	0.54	85.50	0.31	85.50	0.00	0.00	0.00	0.00
Natural gas	0.00	0.00	100.00	98.02	0.00	0.00	20.10	13.24	13.07	98.02	7.45	98.02	0.00	0.00	0.00	0.00
Coal	100.00	50.77	0.00	0.00	0.00	0.00	41.00	13.24	12.98	50.77	7.40	50.77	0.00	0.00	0.00	0.00
Peat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.18	72.08	11.84	84.94	0.00	0.00	0.00	0.00
Wood chips (bioenergy)	0.00	0.00	0.00	0.00	0.00	0.00	1.09	13.24	14.41	91.73	23.25	91.73	0.00	0.00	0.00	0.00
Waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.07	64.77	0.00	0.00	0.00	0.00	0.00	0.00
Hydroelectricity	0.00		0.00		0.00		16.00		17.44		21.41		0.00		0.00	
Wind	0.00		0.00		0.00		0.90		0.68		1.34		100.00		0.00	
Nuclear	0.00		0.00		100.00		14.80		31.63		27.00		0.00		0.00	
Solar PV	0.00		0.00		0.00		0.05		0.00		0.00		0.00		100.00	
Geothermal	0.00		0.00		0.00		0.27		0.00		0.00		0.00		0.00	
Electricity mix	100.00		100.00		100.00		100.00		100.00		100.00		100.00		100.00	

Global warming potential (GWP)

Energy use, manufacturing processes, agriculture and other activities release greenhouse gases to atmosphere, thus strengthening the greenhouse effect and warming up the planet. Although the energy generation processes may be zero emission – such as nuclear electricity, photovoltaic and wind electricity – construction, maintenance and fuel processing cause greenhouse gas emissions.

In this analysis, the following greenhouse gases are taken into account: carbon dioxide, methane, nitrous oxide (N_2O), carbon monoxide and Freons. The global warming effect of aerosols and carbon black is location and time dependent and difficult to quantify, thus they are not included in calculations.

For example, uranium industry has used Freon CFC-114 in the enrichment process and this process is a significant source of Freon emissions. CFC-114 has a global warming impact 10,000 times higher than carbon dioxide. In the analysis, all the emissions are converted to carbon dioxide equivalents and summed together.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

The uncertainties of global warming potential are related to other gases than carbon dioxide (the typical variability is ±35% relative to the CO_2 reference) and aerosols.

Global warming potential is considered highly reliable.

Life-cycle greenhouse gas emissions in different electricity generation stages (well-to-fuel and fuel-to-electricity) and the contributions of various gases to global warming are presented in figures below. The gases are:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Others
    - Carbon monoxide (CO)
    - CFC compounds

- HCFC compounds
- Dichloromethane

The other life-cycle environmental impacts in different electricity generation stages are divided in very much a similar way.

Ozone depletion potential (ODP)

The ozone layer in the stratosphere is an essential component of the Earth's atmosphere. It protects humans, animals and plants from damaging shortwave ultraviolet (UV) radiation. Ozone is produced in the upper stratosphere by the interaction of shortwave solar UV radiation with oxygen. It is destroyed by reactions with certain ozone-depleting substances in the presence of somewhat longer wavelength UV radiation.[5]

The dynamic balance between production and destruction determines the concentration and total amount of ozone in the stratosphere. Anthropogenic emissions of ozone depleting substances, such as chlorine and bromine containing compounds or nitrous oxide, disturb this balance.

Ozone layer depletion is caused by anthropogenic emissions of:

- Chlorofluorocarbons (CFCs)
- Carbon tetrachloride
- Methyl chloroform
- Halons
- Hydrochlorofluorocarbons (HCFCs)
- Hydrobromofluorocarbons (HBFCs)
- Methyl bromide (CH_3Br)
- Nitrous oxide (N_2O)

[5] Velders Guus, Stratospheric ozone depletion, Europe's environment: the third assessment, Environmental assessment report No 10, European Environment Agency, 2002.

These substances are used as solvents, refrigerants, foamblowing agents, degreasing agents, aerosol propellants, fire extinguishers (halons) and agricultural pesticides (CH_3Br). According to new research, nitrous oxide is today top ozone-layer damaging emission and this is projected to remain the case for the rest of this century.[6]

ODP is expressed as CFC-11-equivalent, g CFC-11-eq.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Uncertainties exist in the observations and the models of the depletion of stratospheric ozone layer.

Acidification potential (AP)

Incineration processes in energy generation and fuel combustion in transportation release sulphur oxide (SO_2) and nitric oxides (NO_x) into the atmosphere. Acid rain is produced when sulphur dioxide and nitrogen oxides are present in moisture in the atmosphere. Sulphur oxides and nitrous oxides are removed from the atmosphere through wet and dry deposition, causing acidification of water and soil. Ammonia, hydrogen sulphide and hydrogen chloride are also causing acidification of the environment.

Industrial processes, energy generation, transportation and agriculture are the most significant sources of acidification. Acidification affects human health, wildlife and vegetation and causes damage to anthropogenic structures and materials.

AP is expressed as SO_2 equivalent, kg SO_2e.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

[6] Nitrous oxide is now top ozone-layer damaging emission, European Commission DG ENV, News Alert Issue 178, December 2009.

Acidification potential is considered reliable.

Photochemical ozone creation potential (POCP)

Photochemical smog is formed when primary pollutants react with ultraviolet light to create a variety of toxic and reactive compounds. The two major primary pollutants, nitrogen oxides and VOCs (volatile organic compounds), combine to change in sunlight in a series of chemical reactions to create secondary pollutants. The secondary pollutant that causes the most concern is the ozone that forms at ground level.

Photochemical smog is harmful to human health, ecosystems, materials, vegetation and crops. Emissions that lead to photochemical smog are measured in kg ethylene equivalents.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Photochemical ozone creation potential is a very coarse approximation of the actual phenomena. It has very low reliability.

Air toxicity (AT)

The air toxicity indicator (AT) is representing the air toxicity in a human environment, taking into account the usually accepted concentrations tolerated for several gases and the quantity released. The given indication corresponds to the air volume necessary to dilute "contaminated air".[7]

A gram of CO_2 requires 125 m^3 to dilute to an acceptable level while a gram of mercury requires 1.4 million m^3.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

[7] EIME, Environmental Improvement Made Easy, Life cycle analysis and ecodesign software, Indicators manual, Bureau Veritas CODDE, July 2009.

This method has limitations. Acceptable levels vary from country to country and are subject to public opinions and political decisions.

Water toxicity (WT)

The water toxicity indicator (WT) is representing the water toxicity. This indicator takes into account the usually accepted concentrations tolerated for several substances and the quantity released. The given indication corresponds to the water volume necessary to dilute "contaminated water".

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Water toxicity indicator is reliable/very reliable.

Hazardous waste production (HWP)

Hazardous waste production (HWP) calculates the quantity of hazardous waste produced for a given product during its life cycle. It is expressed as kg hazardous waste.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Hazardous waste production indicator has low reliability.

Eutrophication potential (EP)

Human activities – industry, energy generation, transportation, silviculture, agriculture and land use changes – have accelerated the rate and extent of eutrophication.

Emissions of ammonia, nitrates, nitrogen oxides and phosphorous to air or water all have an impact on eutrophication. The eutrophication potential is expressed using the reference unit, kg PO4 equivalents.

Generally, there are two kinds of uncertainty: the calculation modelling (used to describe a physical phenomenon) and the reliability and accuracy of the inventory dataset.

Eutrophication potential has very low reliability.

Particulate emissions

Air pollution is caused by the presence of polluting substances such as fine particulates, sulphur compounds, nitrous oxides, volatile hydrocarbons and ground-level ozone. At high concentrations, these substances have effects on health and environment.

Burning fossil fuels and biomass has increased the concentrations of particulate matter in the air. Particulate matter is a mixture of solid particles and liquid droplets that are suspended in the air. Particulate matter is composed of a mixture of particles directly emitted into the air and particles formed in the air from the chemical transformation of gaseous pollutants (secondary particles). Particle size can range from 0.001 to 500 μm. Size of fine particulate is less than 2.5 μm.

SO_2 emissions

Fuels contain varying amounts of sulphur. In combustion processes sulphur is converted into sulphur dioxide (SO_2). In the atmosphere, sulphur dioxide reacts with moisture in the air to form sulphurous acid (H_2SO_3) or sulphuric acid (H_2SO_4) causing acid rain.

Sulphur dioxide emissions have adverse effects on human health, environment and anthropogenic constructions and materials. Sulphur dioxide emissions can be reduced by reducing energy consumption, switching to cleaner and more efficient energy production technologies and fuels and cleaning fuel gases.

NO_x emissions

In combustion processes, nitrogen of the fuel and also of the combustion air reacts to a certain amount with oxygen of the combustion air and forms nitric oxides (NO_x). The amount of nitric oxides formed can be affected by controlling the combustion process.

Nitric oxides form nitric acid when dissolved in atmospheric moisture, forming a component of acid rain and causing acidification and eutrophication of soils and waters.

Methane emissions

Methane (CH_4) is emitted by natural sources such as wetlands. Globally, over 60% of total methane emissions come from human activities. Methane is emitted from natural gas systems and other industries, agriculture (such as the raising of livestock) and waste management activities.[8]

Gram for gram, the comparative impact of methane on climate change is 21 times greater than carbon dioxide over a 100-year period[9]. Methane emissions also affect ground-level ozone formation.

N_2O emissions

Nitrous oxide (N_2O) is a major greenhouse gas and air pollutant. Over a 100-year period, it has 298 times more impact per unit mass than carbon dioxide[9].

Human activities have more than doubled the global nitrogen inputs to ecosystems and accelerated the nitrogen cycle. Also N_2O emissions have increased substantially over the last century because of human actions. Human-related sources are responsible for 38% of total N_2O emissions.

Energy generation, transportation, agriculture and industry are major sources of N_2O. Nitric acid and adipic acid production are the main industrial sources of N_2O emissions.

Non-methane hydrocarbon emissions

Hydrocarbon emissions affect both air and water quality. Many volatile reactive hydrocarbons facilitate the photochemical creation of ground-level ozone.

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[8] Methane emissions, U.S. Environmental Protection Agency, Washington, DC, USA, [http://epa.gov/climatechange/ghgemissions/gases/ch4.html], 11.06.2014.

[9] Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

CO emissions

Carbon monoxide (CO) is formed by incomplete combustion. It affects air quality and contributes to global warming. Carbon monoxide is 1.9 times more potent greenhouse gas than carbon dioxide (gram for gram).

Creation of high-level radioactive waste (HLW)

Radioactive waste is created at every step of the nuclear fuel cycle from uranium mining to nuclear fission in reactors. The high-level radioactive waste (HLW) is mostly spent nuclear fuel from commercial power plants.

High-level radioactive wastes are hazardous to humans and other life forms because of their high radiation levels that are capable of producing fatal doses during short periods of direct exposure[10]. The amount of time high-level waste remains dangerous is thousands to hundreds of thousands of years. Deep geological repositories are being considered for the long-term management of the high-level radioactive wastes.

Creation of medium- and low-level radioactive waste (MLW+LLW)

Medium-level radioactive waste (MLW) (containing higher concentrations of beta/gamma contamination and sometimes alpha emitters) originates from routine power station maintenance operations, for example used ion exchange resins and filter cartridges.

Low-level radioactive waste (LLW) consists of trash and debris from routine nuclear facility operations and decommissioning.

Petroleum consumption

Petroleum is a nonrenewable resource that is used in practically every human activity. For about 150 years, the consumption of petroleum has increased year after year. This will not be

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[10] Radioactive Waste, The U.S. Nuclear Regulatory Commission, http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/radwaste.html, 11.06.2014.

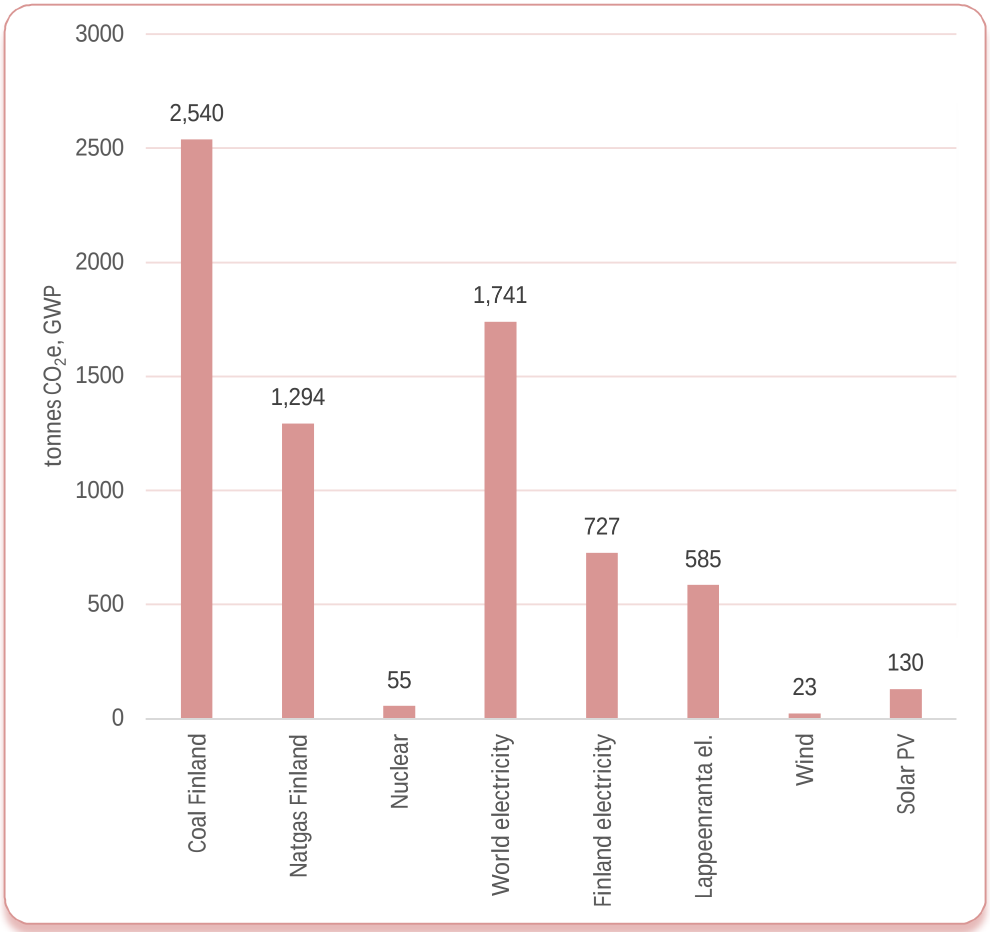
possible forever, and we must decrease our petroleum intensity in all sectors of our society. The petroleum intensities of the energy systems vary significantly.

Energy depletion

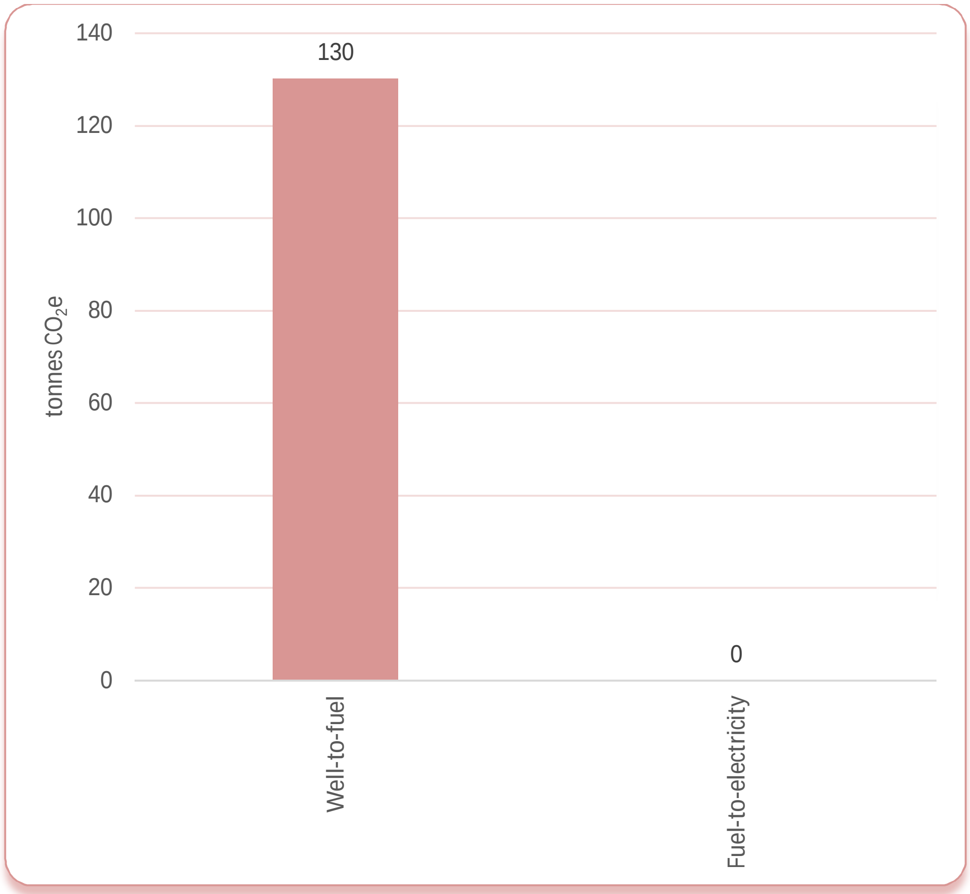
Energy depletion gives all the energy inputs needed during the whole life cycle. Energy inputs may be either renewable or nonrenewable. Primary energy resources are fossil fuels, hydroelectricity and nuclear power.

Typically the energy inputs have a direct effect on the quantities of many environmental impacts, such as global warming or acidification.

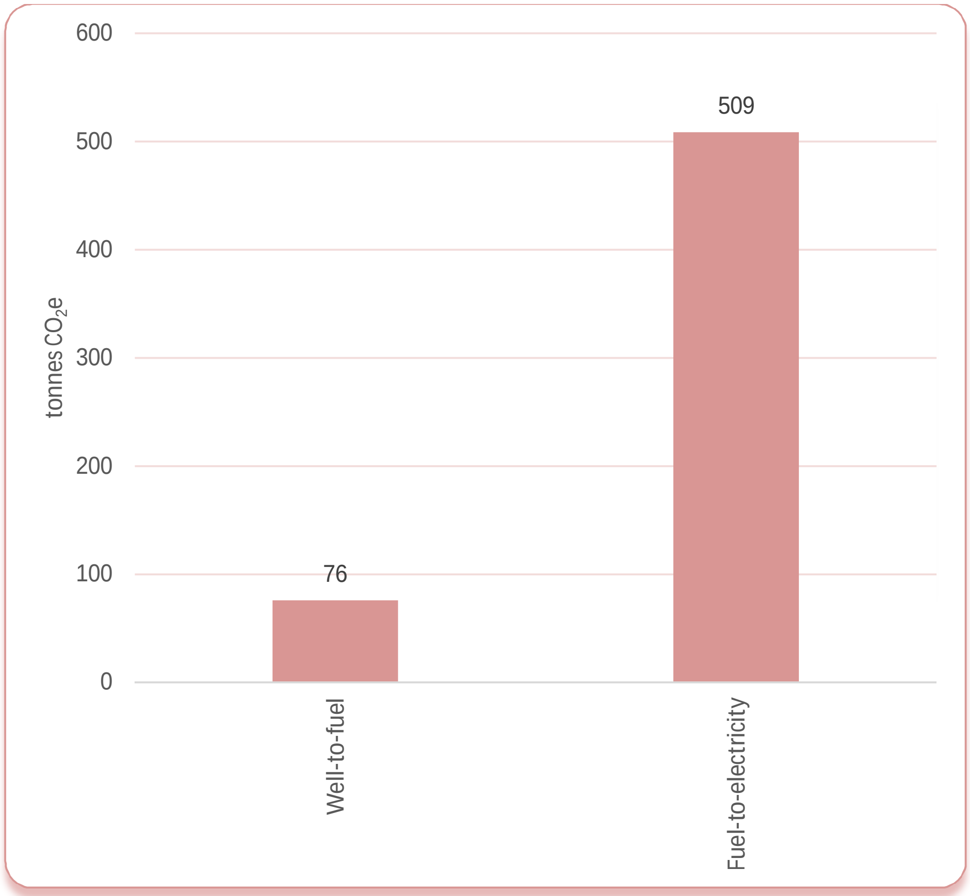
Results



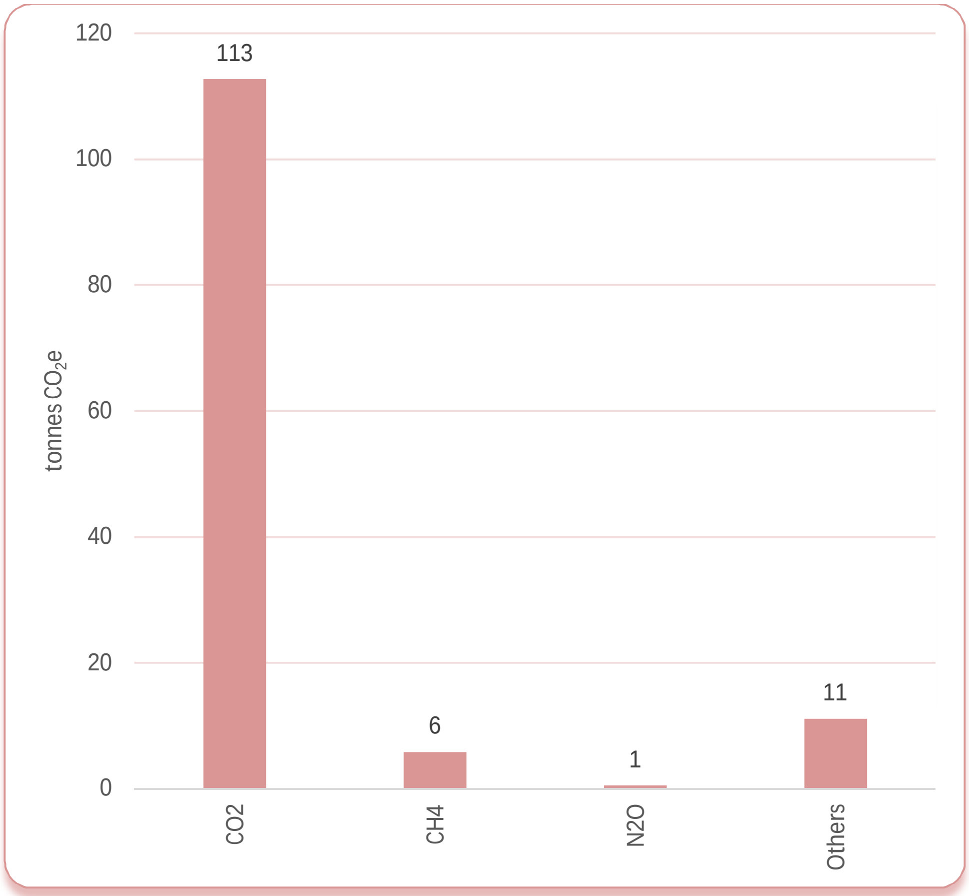
The life-cycle global warming potential (GWP, expressed as carbon dioxide equivalent) of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the global warming potentials of various energy systems generating the same amount of electricity.



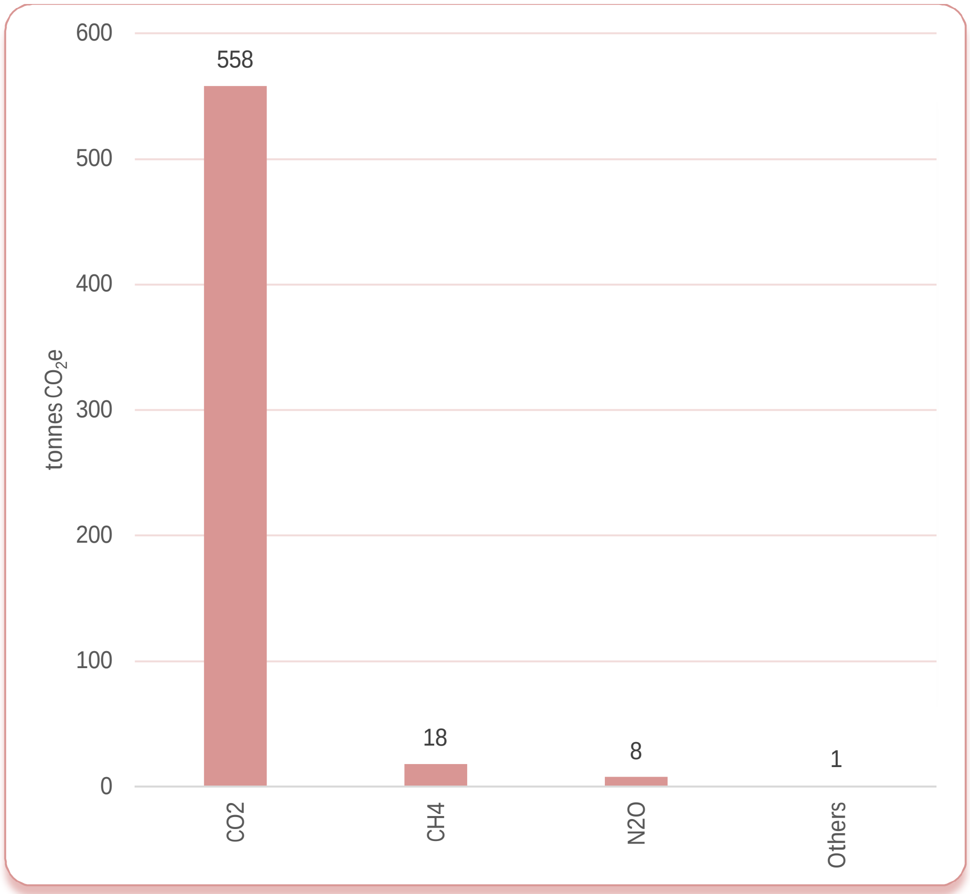
The division of life-cycle carbon dioxide equivalents of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system.



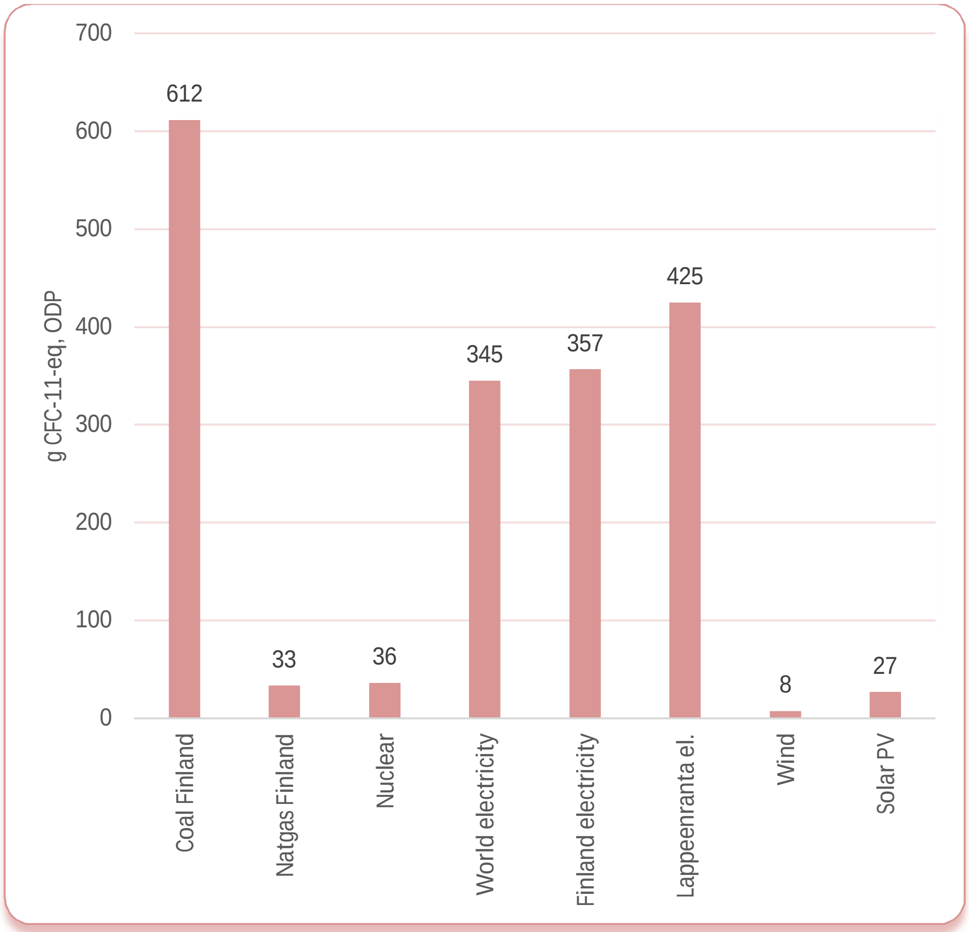
The division of life-cycle carbon dioxide equivalents of Lappeenrannan Energia electricity mix producing the same amount of electricity as the Huhtiniemi photovoltaic system.



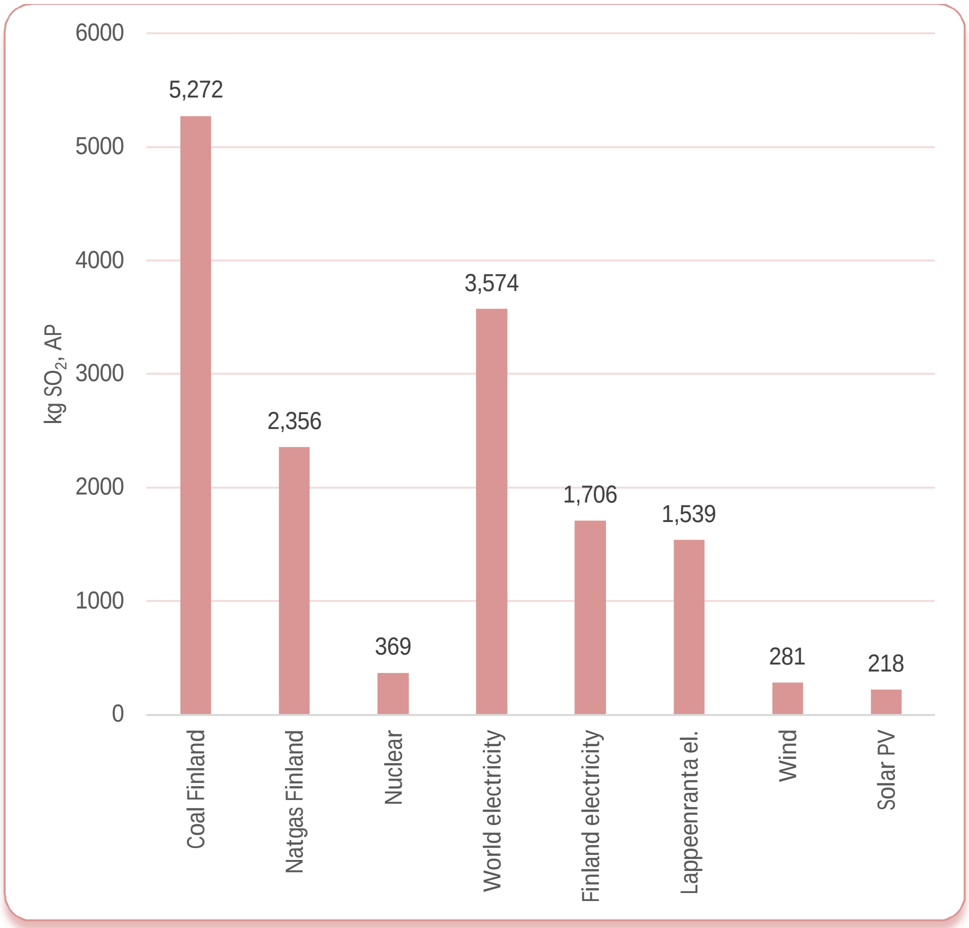
The life-cycle emissions of different greenhouse gases for the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system.



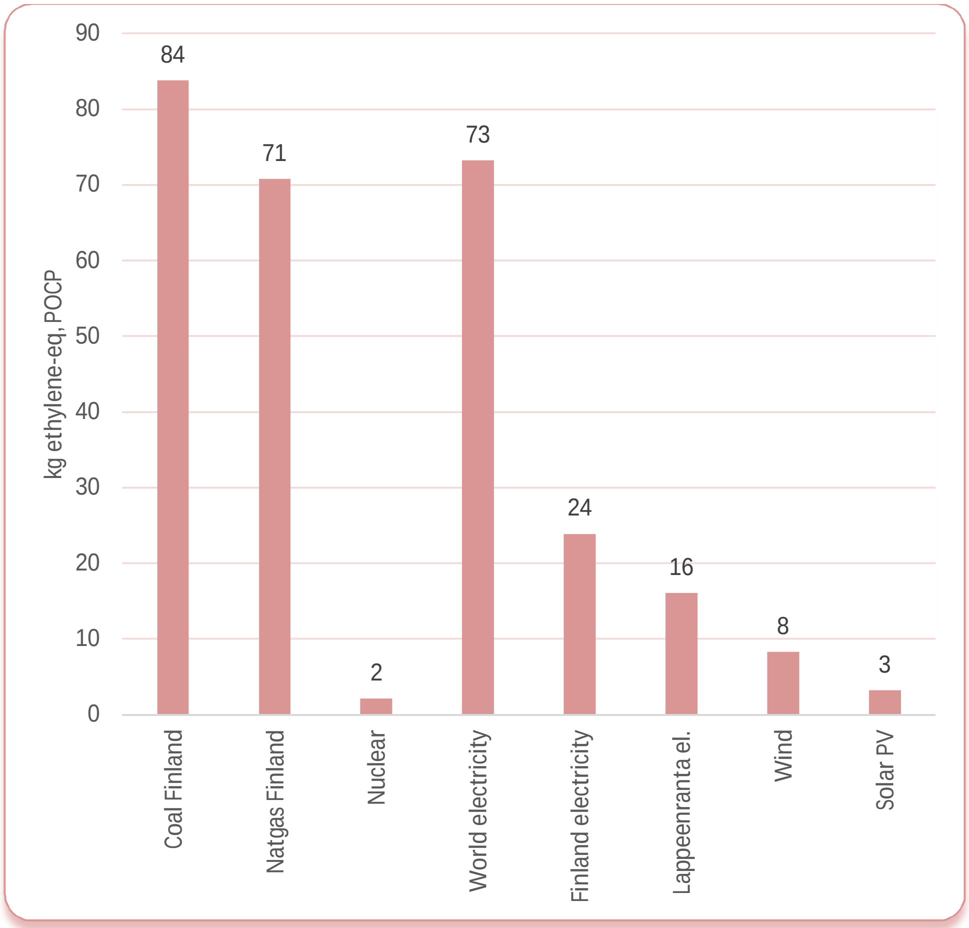
The life-cycle emissions of different greenhouse gases for the Lappeenrannan Energia electricity mix producing the same amount of electricity as the Huhtiniemi photovoltaic system.



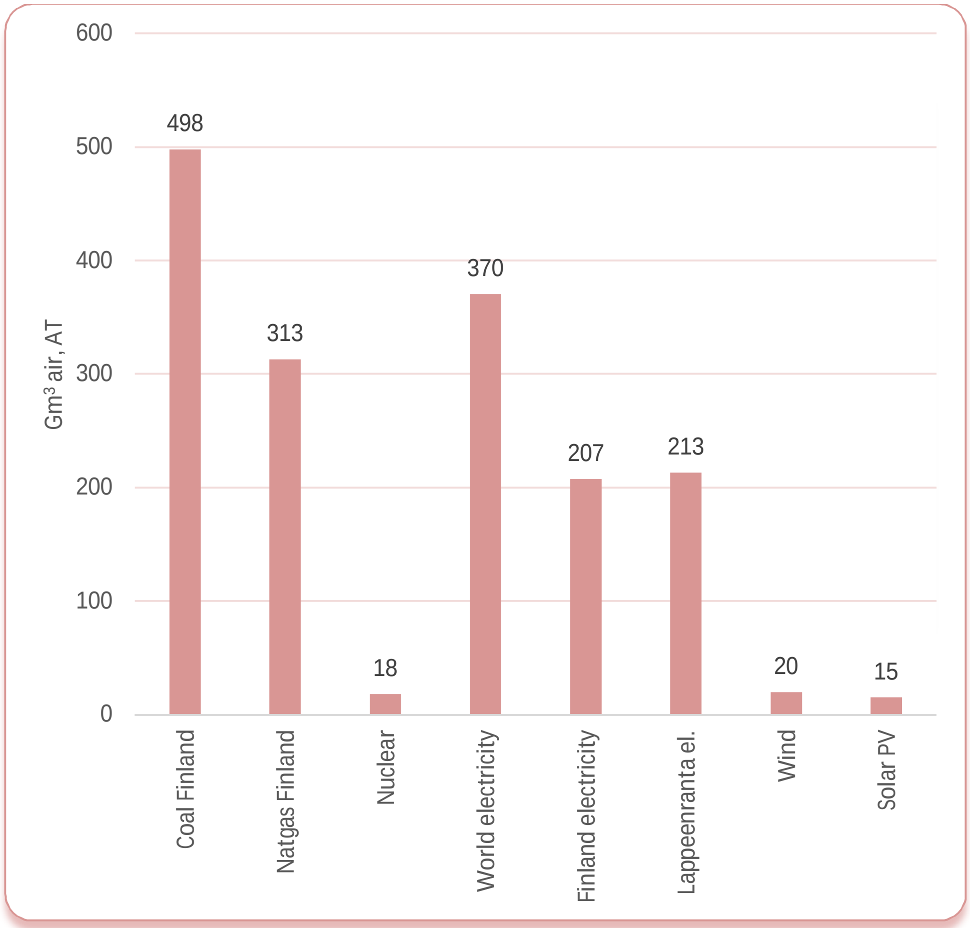
The life-cycle ozone depleting potential (ODP, expressed as CFC-11-equivalent) of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the ozone depleting potentials of various energy systems generating the same amount of electricity.



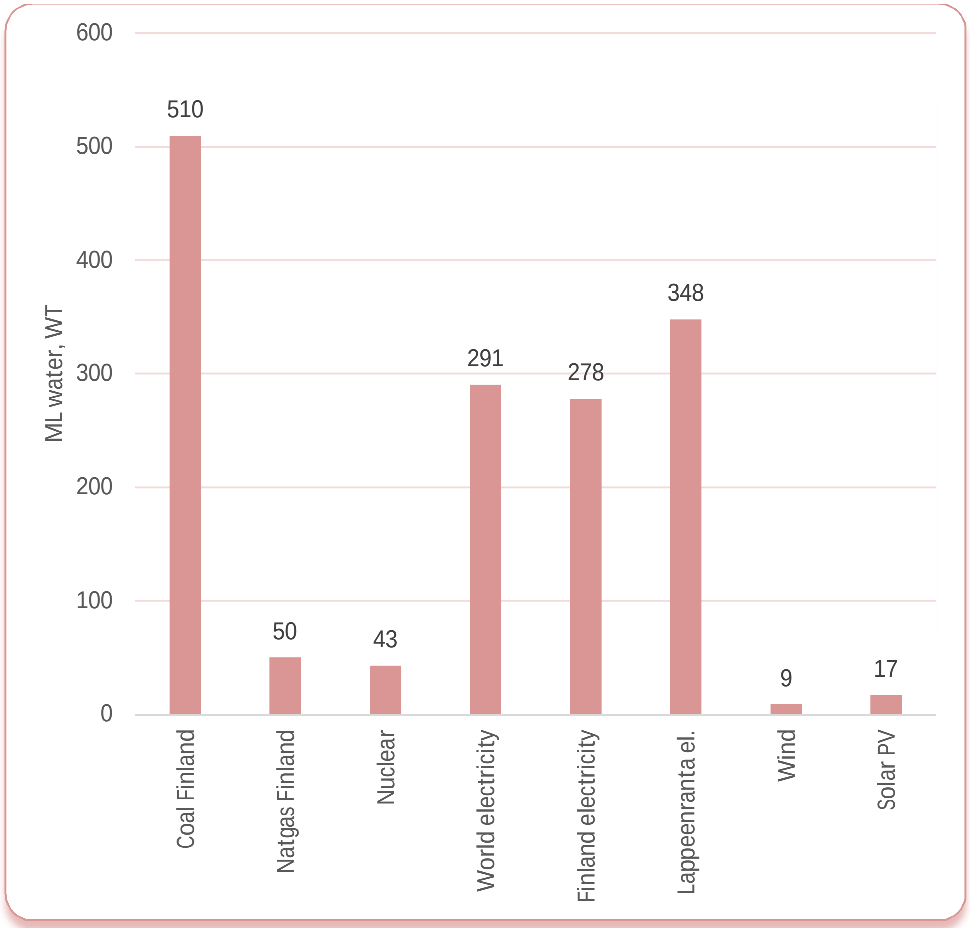
The life-cycle acidification potential (AP, expressed as kg SO_2e) of the Huhtiniemi 153.8 kWp (1000 m^2 solar panels) rooftop photovoltaic system and the acidification potentials of various energy systems generating the same amount of electricity.



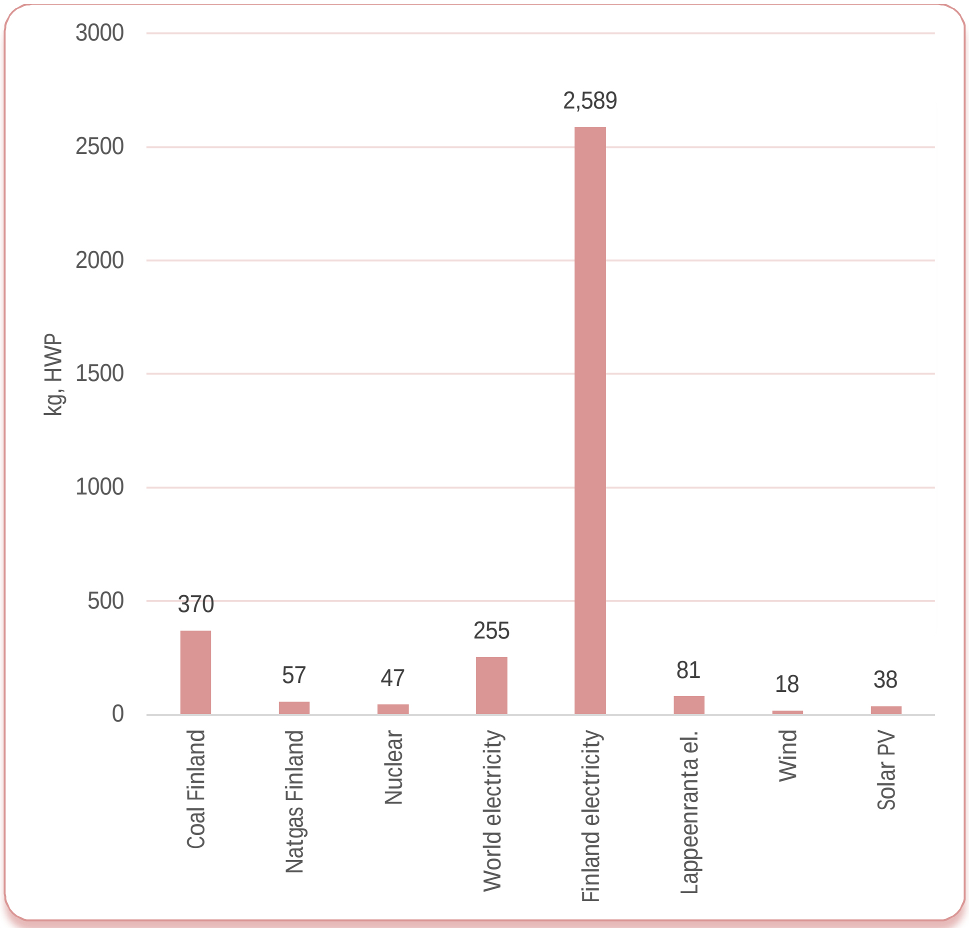
The life-cycle photochemical ozone creation potential (POCP, expressed as kg ethylene-eq) of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the photochemical ozone creation potentials of various energy systems generating the same amount of electricity.



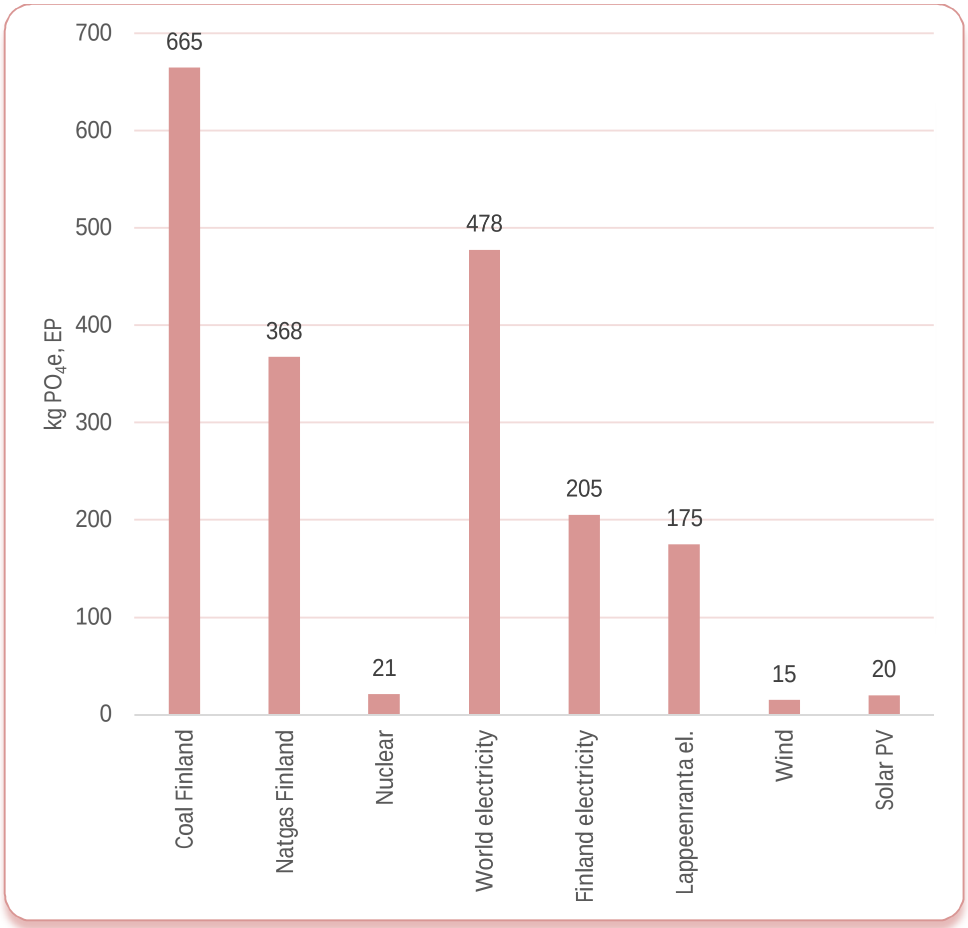
The life-cycle air toxicity (AT, expressed as billion m³ air) of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the air toxicities of various energy systems generating the same amount of electricity.



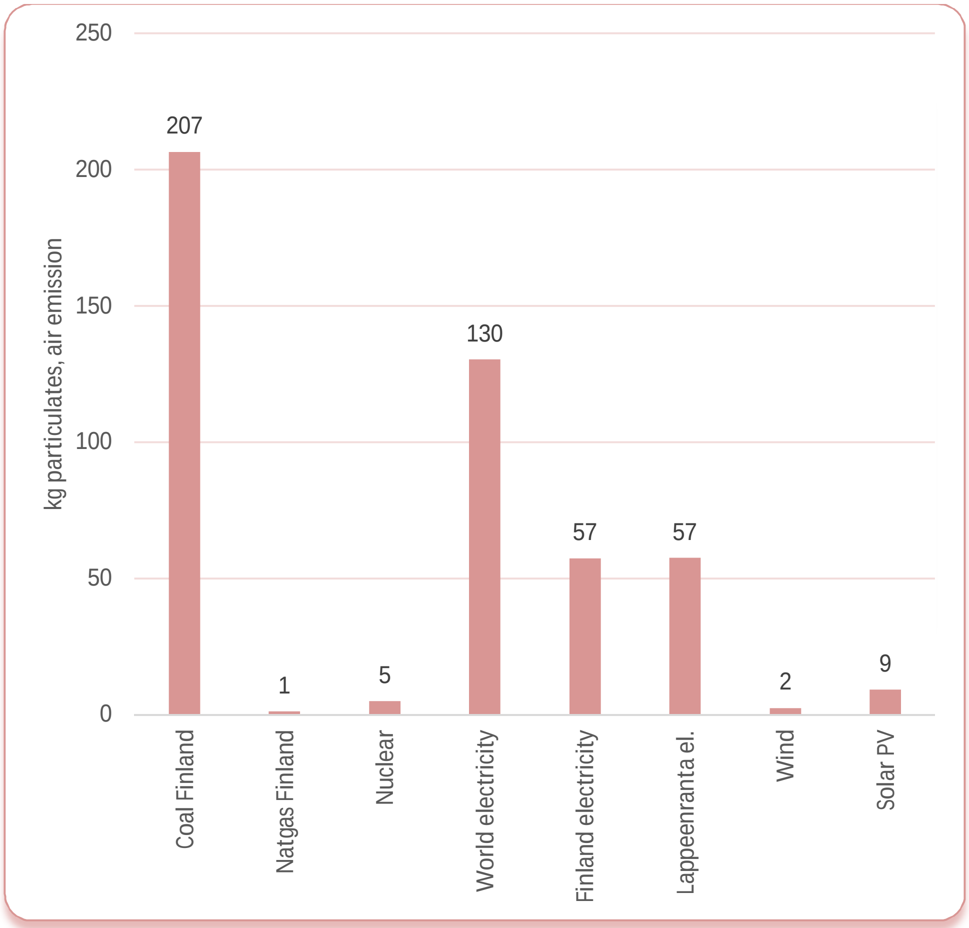
The life-cycle water toxicity (WT, expressed as million liters water) of the Huhtiniemi 153.8 kWp (1000 m^2 solar panels) rooftop photovoltaic system and the water toxicities of various energy systems generating the same amount of electricity.



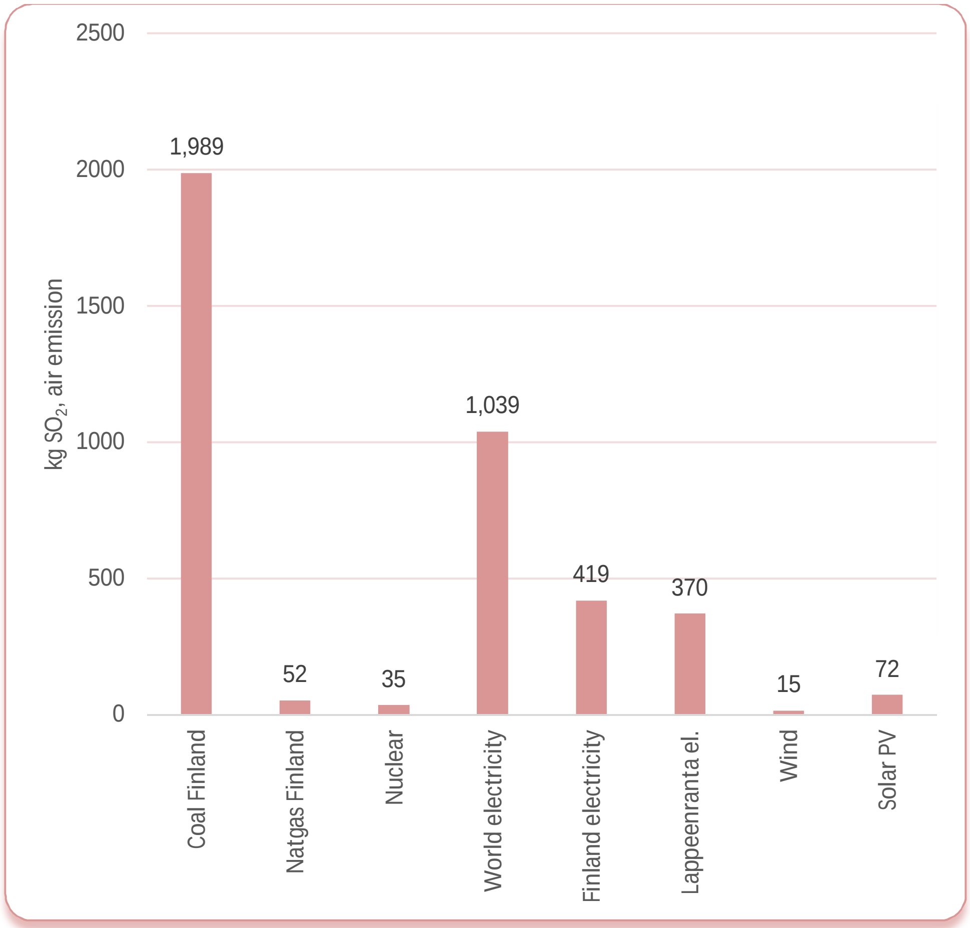
The life-cycle hazardous waste production (HWP, expressed as kg hazardous waste) of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the hazardous waste production of various energy systems generating the same amount of electricity.



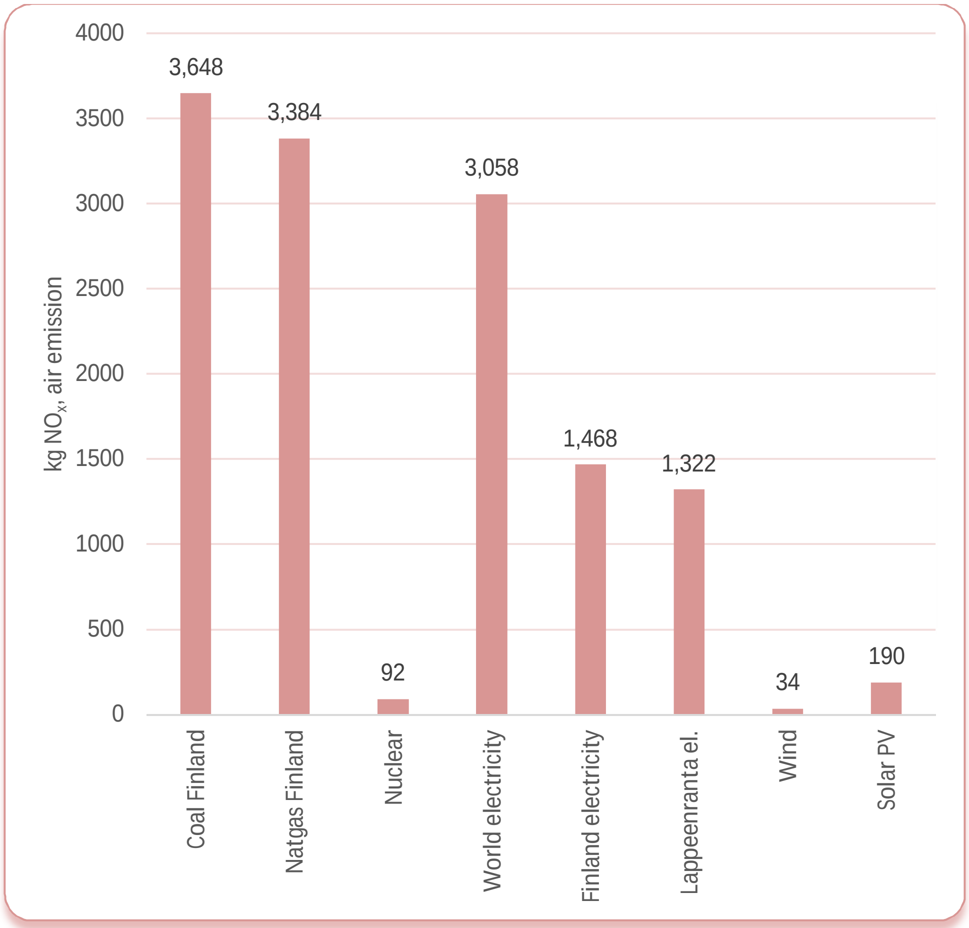
The life-cycle eutrophication potential (EP, expressed as kg PO_4e) of the Huhtiniemi 153.8 kWp (1000 m^2 solar panels) rooftop photovoltaic system and the eutrophication potentials of various energy systems generating the same amount of electricity.



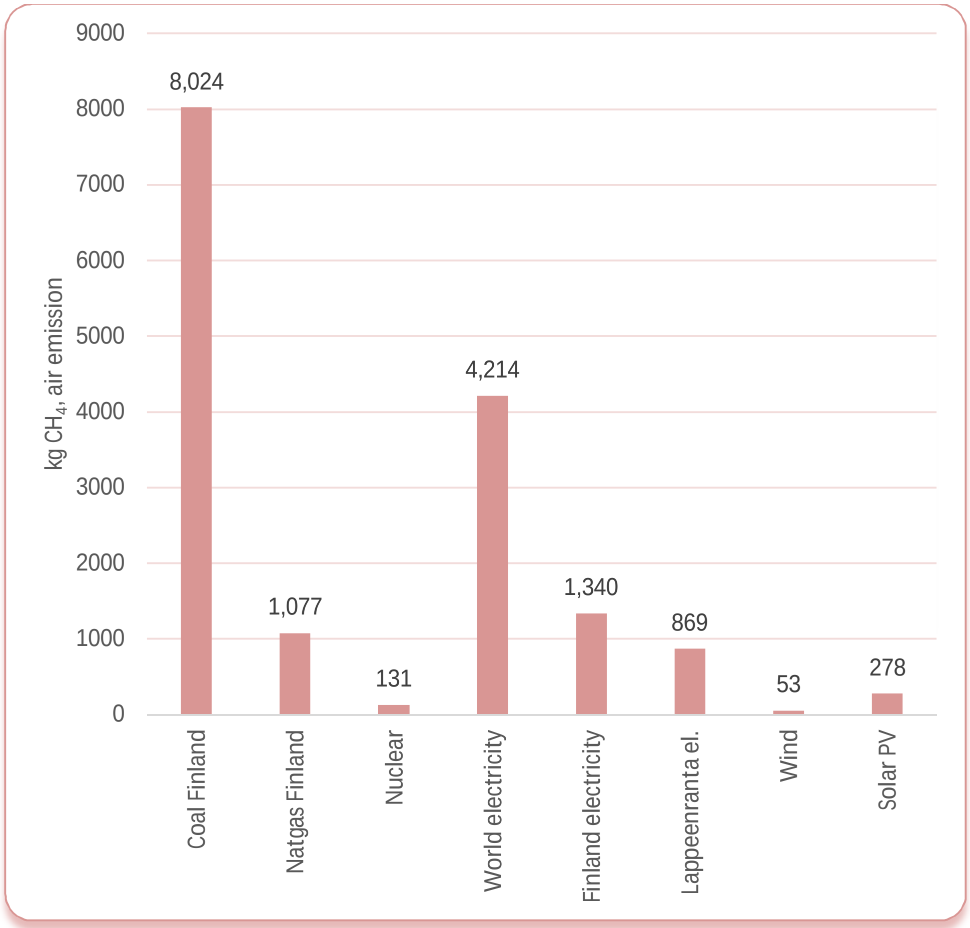
The life-cycle particulate emissions of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the particulate emissions of various energy systems generating the same amount of electricity.



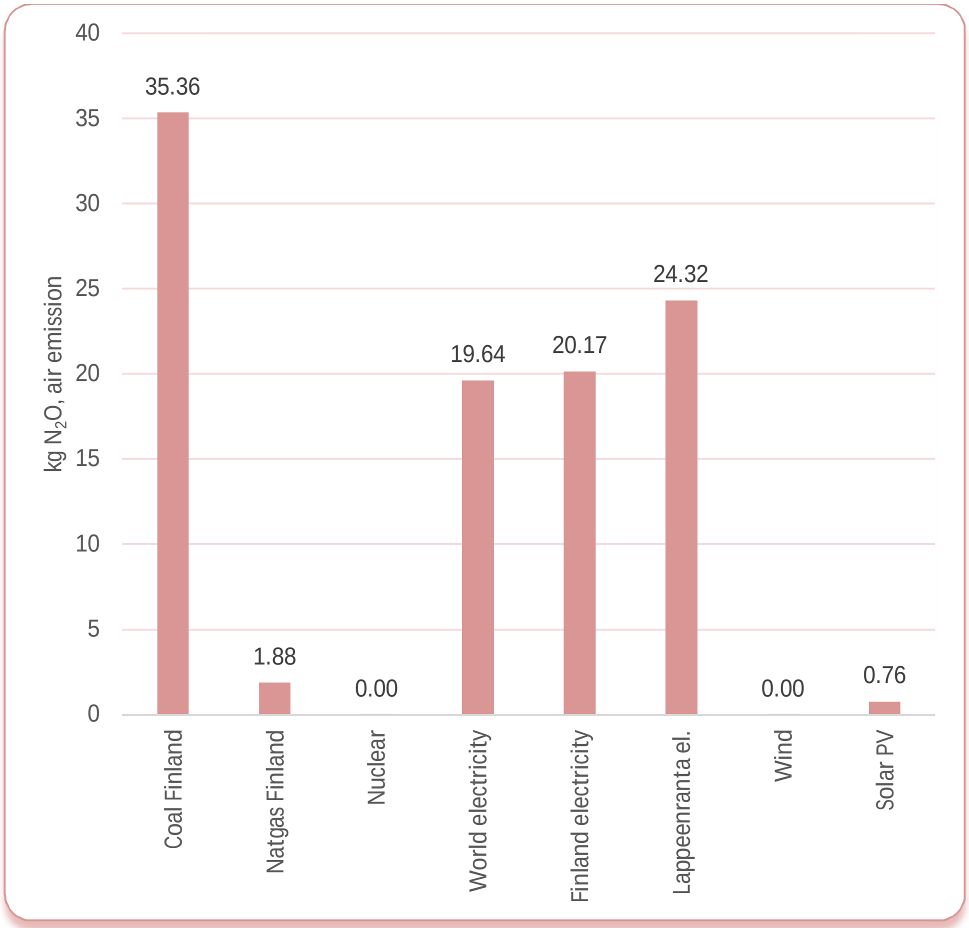
The life-cycle sulphur dioxide emissions of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the sulphur dioxide emissions of various energy systems generating the same amount of electricity.



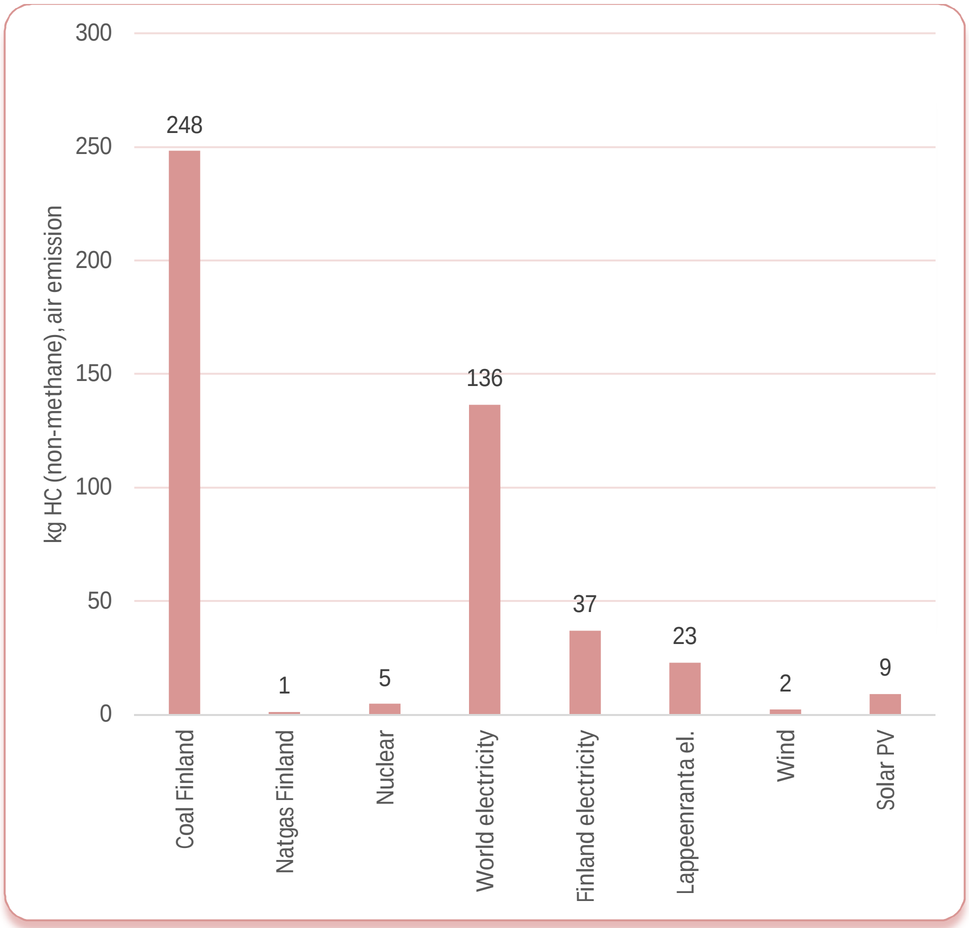
The life-cycle nitric oxide emissions of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the nitric oxide emissions of various energy systems generating the same amount of electricity.



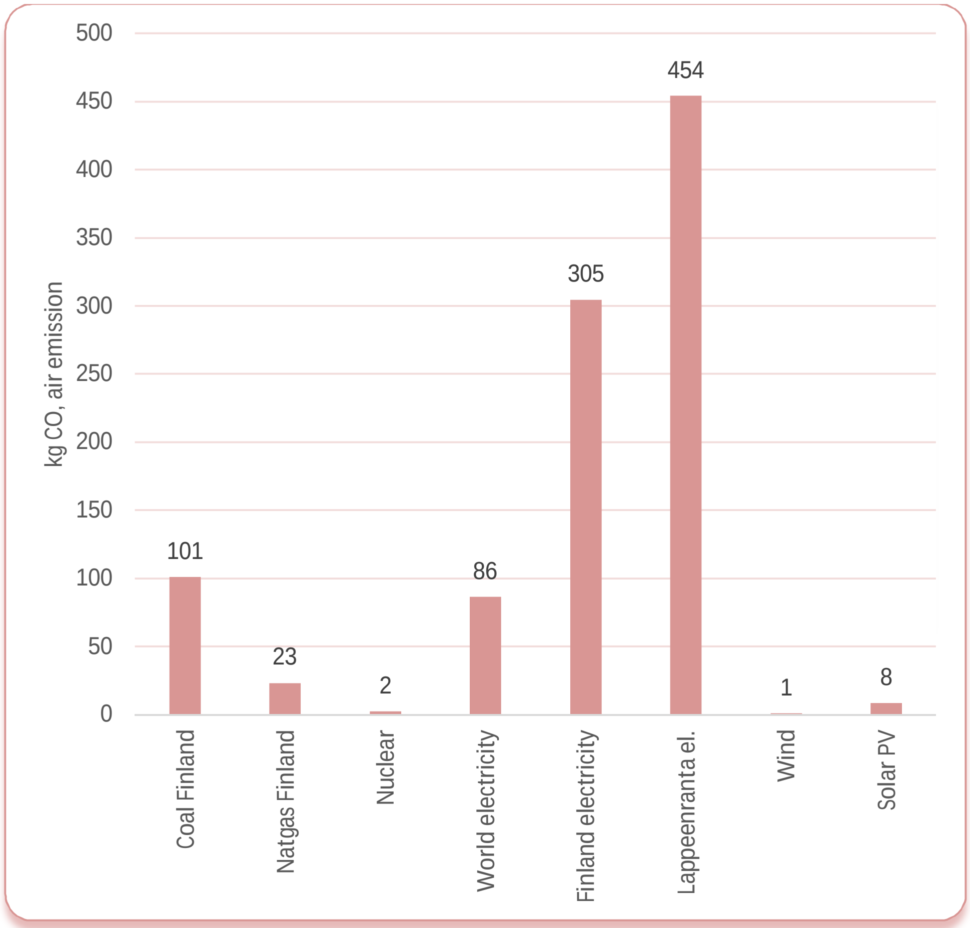
The life-cycle methane emissions of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the methane emissions of various energy systems generating the same amount of electricity.



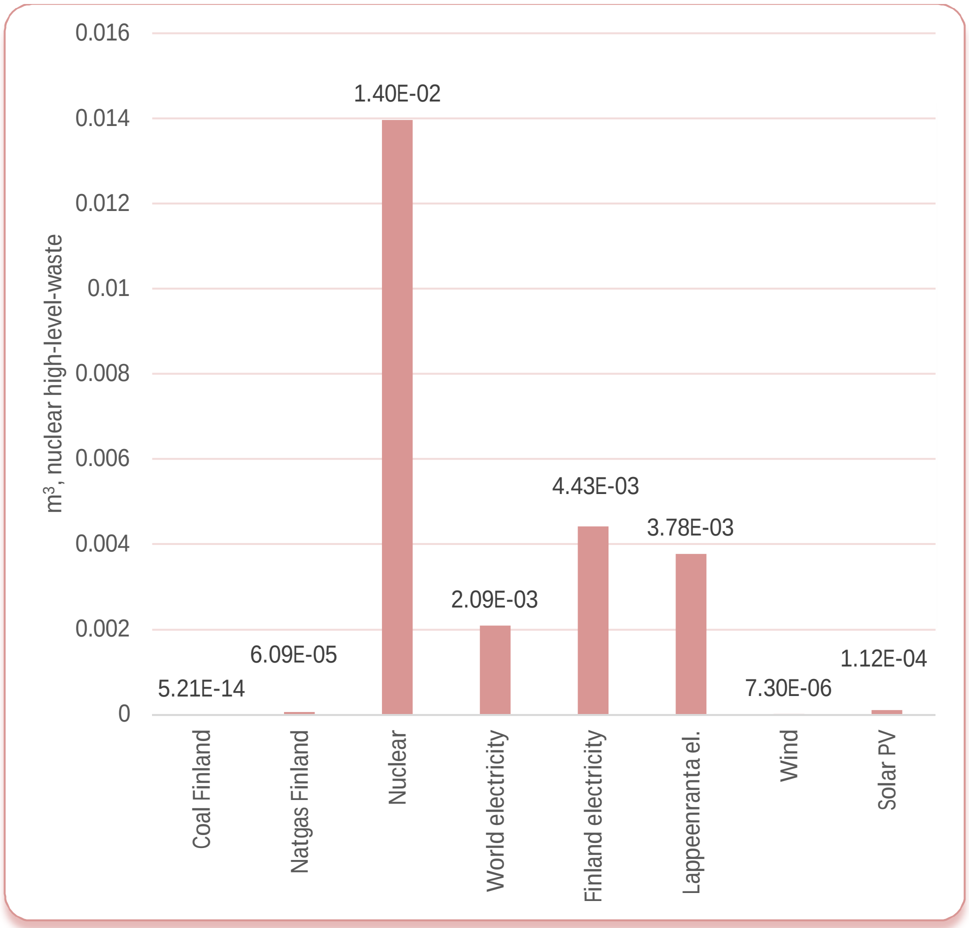
The life-cycle nitrous oxide emissions of the Huhtiniemi 153.8 kWp (1000 m^2 solar panels) rooftop photovoltaic system and the nitrous oxide emissions of various energy systems generating the same amount of electricity.



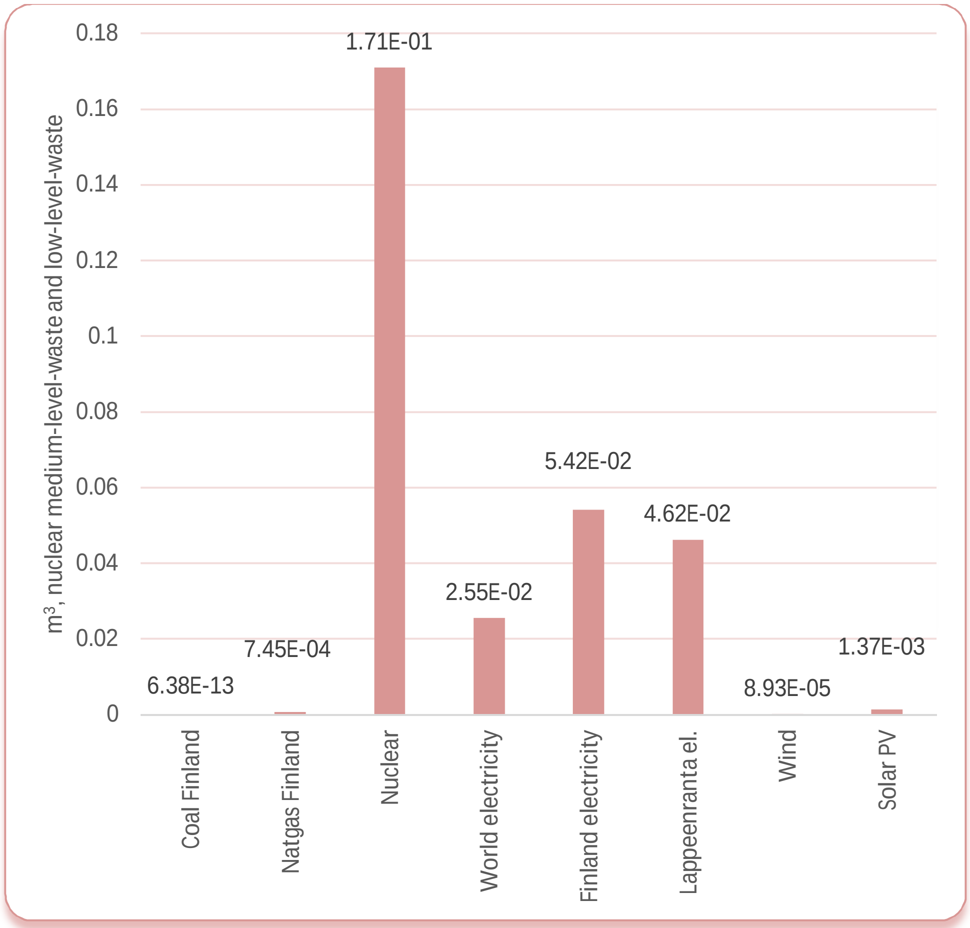
The life-cycle non-methane hydrocarbon emissions of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the non-methane hydrocarbon emissions of various energy systems generating the same amount of electricity.



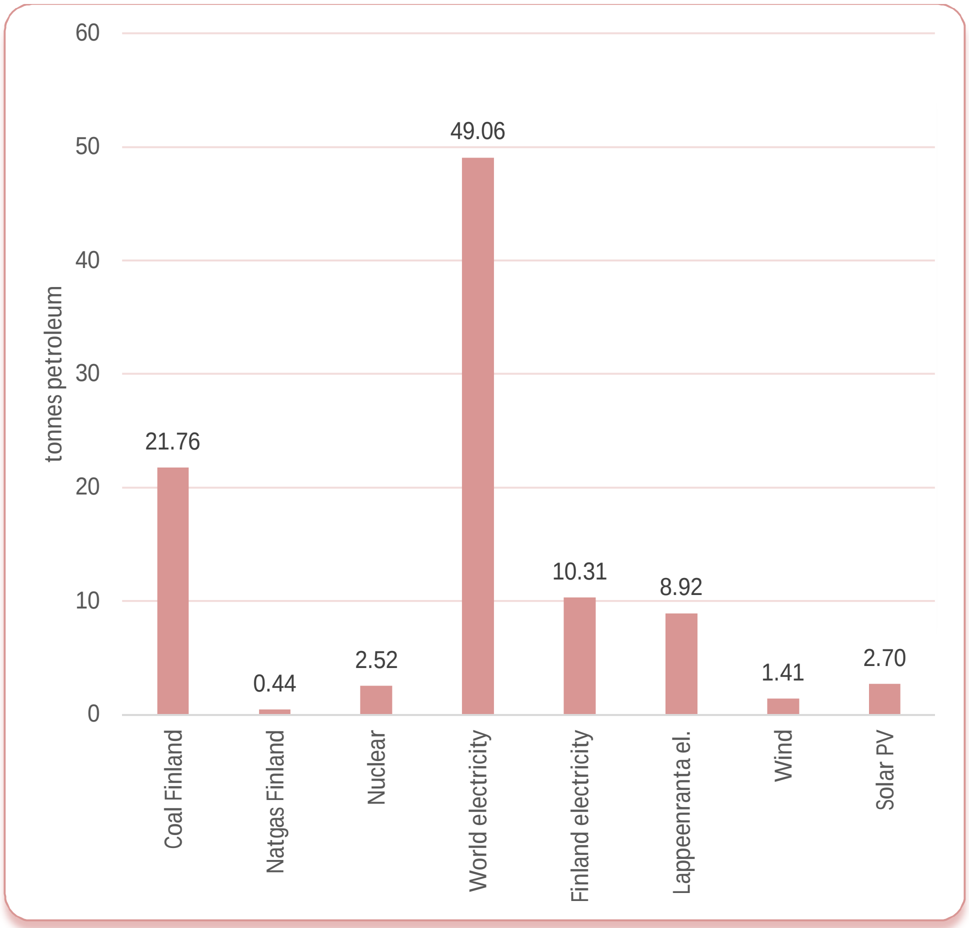
The life-cycle carbon monoxide emissions of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the carbon monoxide emissions of various energy systems generating the same amount of electricity.



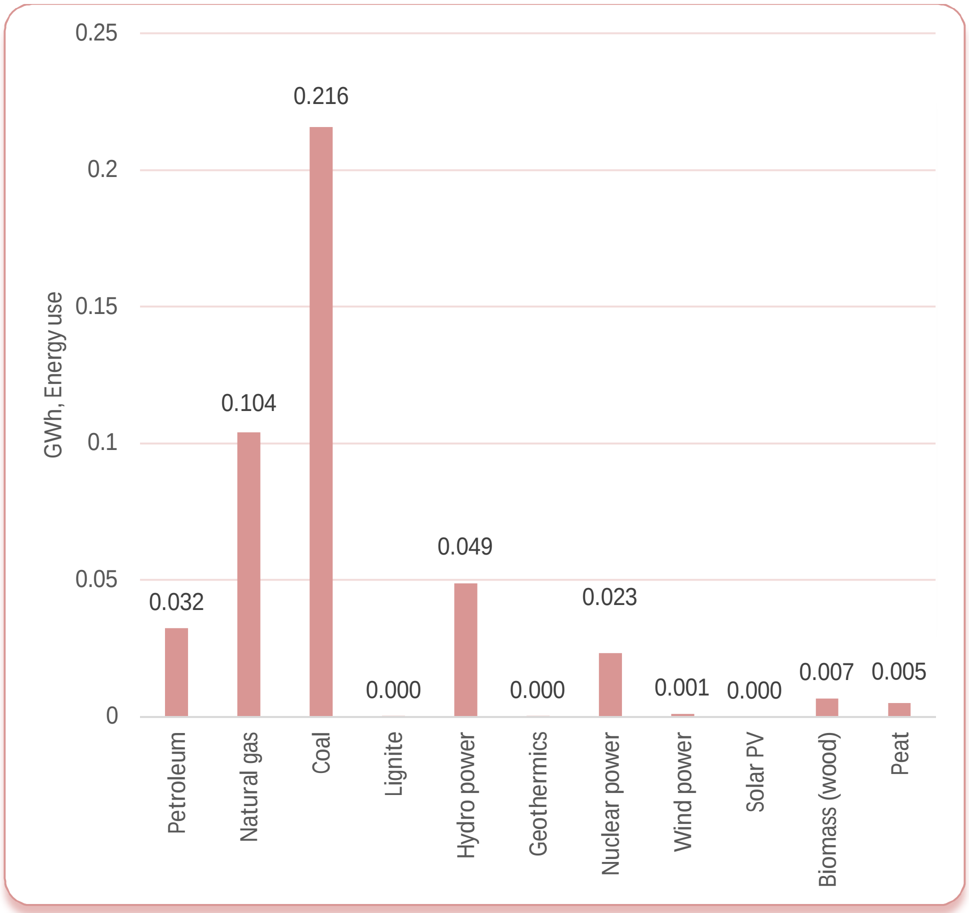
The life-cycle creation of high-level radioactive waste of the Huhtiniemi 153.8 kWp (1000 m^2 solar panels) rooftop photovoltaic system and the creation of high-level radioactive waste of various energy systems generating the same amount of electricity.



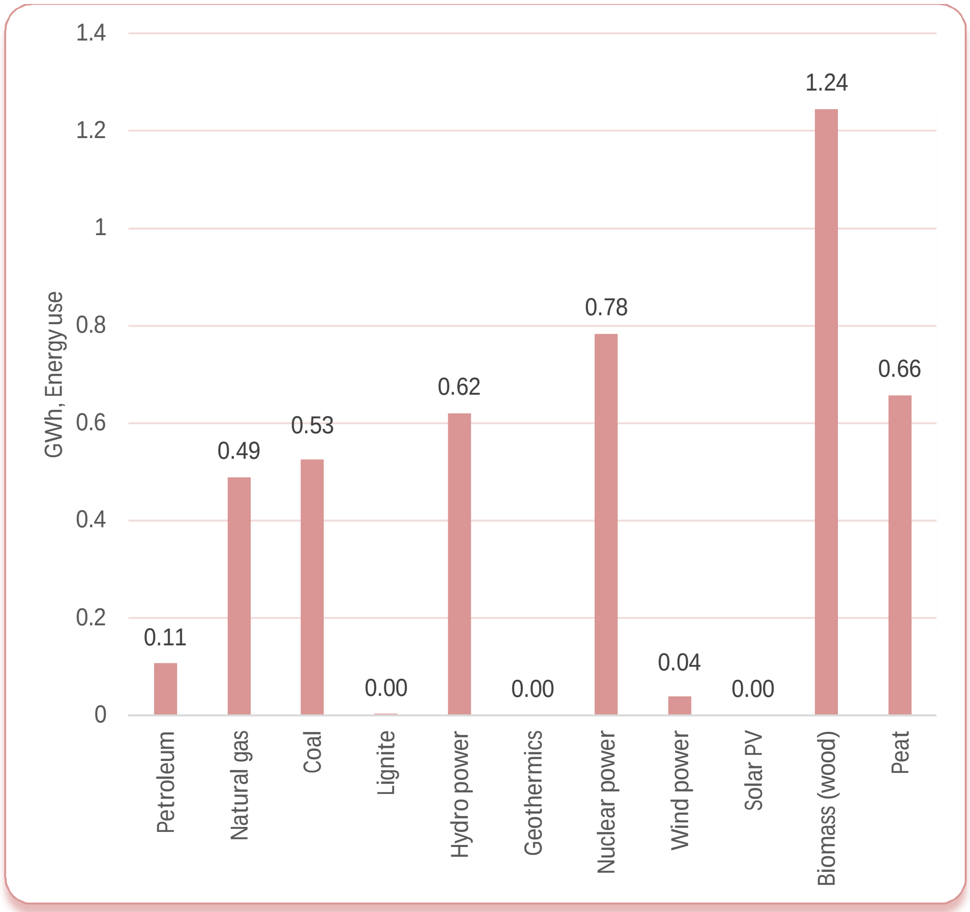
The life-cycle creation of medium- and low-level radioactive waste of the Huhtiniemi 153.8 kWp (1000 m^2 solar panels) rooftop photovoltaic system and the creation of medium- and low-level radioactive waste of various energy systems generating the same amount of electricity.



The life-cycle petroleum consumption of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system and the petroleum consumption of various energy systems generating the same amount of electricity.



The life-cycle energy depletion impact of the Huhtiniemi 153.8 kWp (1000 m² solar panels) rooftop photovoltaic system.



The life-cycle energy depletion impact of Lappeenrannan Energia grid electricity. The electricity amount is the same as in the Huhtiniemi 153.8 kWp rooftop photovoltaic system (whole life cycle).

153.8 kWp (1000 m²) photovoltaic investment

The capital investment appraisal is based on the large photovoltaic system (32 kWp) with 208 m² solar panels[11]. This system is scaled up to a 1000 m² 153.8 kWp photovoltaic system. The price of the 153.8 kWp photovoltaic system is linearly extrapolated from the 32 kWp system.

[11] www.photovoltaik-shop.com

The price of the 153.8 kWp photovoltaic system (panels, inverter and accessories) was found to be 186,507 euros. Assembling costs were estimated to be 24,000 euros, and the total investment is thus about 210 thousand euros. The 153.8 kWp photovoltaic system consists of:

- 615 photovoltaic panels (Heckert Nemo P 250 poly, á 1.625 m^2, 250 kWp, 17.7 kg)
- 615 support brackets (IBC TopFix 200)
- 1 inverter (29,251 euros)
- 3125 m cable (Solarkabel IBC Flexi Sun 1 x 6 mm^2)

Photovoltaic panel Heckert Nemo P 250 poly.

Support bracket IBC TopFix 200.

Solar inverter PowerOne PVI-Central-165 TL.

Cable Solarkabel IBC Flexi Sun 1 x 6 mm².

The Finnish government gives investment subsidy to renewable energy investments in 2014[12]. Renewable energy investments and energy efficiency-enhancing investments using conventional technologies get a 30% investment subsidy (photovoltaic power is in this category). After this investment subsidy, the total investment to the 153.8 kWp photovoltaic system is 147,355 euros.

In the calculations, the life-cycle of the photovoltaic system is estimated to be 30 years[13]. Photovoltaic systems are virtually maintenance-free and no costs to maintenance are allocated. After about 15 years, the inverter is renewed (29,251 euros).

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[12] Investointituet uusiutuvalle energialle, Motiva, www.motiva.fi/toimialueet/uusiutuva_energia/uusiutuva_energia_suomessa/uusiutuvan_energian_tuet/ investointituet_uusiutuvalle_energialle, (in Finnish).

[13] Aurinkosähköopas tamperelaisille, ECO_2, Ekotehokas Tampere 2020.

The modules will be performing at 100% of nominal power capacity the first five years, at 90% of nominal power capacity from five to ten years, at 80% of nominal power capacity from ten to twenty five years and at 70% of nominal power capacity the last five years.

In Finland, the average conditions for photovoltaic power are about the same as in Germany (longer days at summer, shorter days at winter). In Germany using the annual photovoltaic electricity production figures[14], the life-cycle electricity production for a photovoltaic module is 2896 kWhe/m^2 (30 year life cycle).

In Finland, the electricity tax is 2.11172 cents/kWhe, and for the photovoltaic electricity the tax must either be paid or not (the situation is unclear) [15]:

”If it is possible for a 50–2000 kVA system (even in theory) to feed electricity to the grid, the system must be registered to the electricity tax registry. Tax must be paid even though the electricity is self-generated and used at the site of generation.

Another interpretation is that the months with zero-feed to the grid are completely free of electricity tax.

Below the investment calculations are done for two cases:

1. It is assumed that electricity tax is paid during the whole life cycle.
2. It is assumed that no electricity tax is paid during the life cycle.

The annual revenue is calculated using the electricity price of Lappeenrannan Energia Oy, 13.05172 cents/kWhe:

- 6.9 cents/kWhe electricity
- 4.04 cents/kWhe electricity transmission

[14] Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit , December 2013.

[15] Taxation of 50 kVA – 2000 kVA photovoltaic power plants (in Finnish), Soleras, http://www.soleras.fi/Pages%20FI/Verotus.html.

- 2.11172 cents/kWhe electricity tax

Electricity generation and revenues during the life cycle are as follows:

- Years 0–5:
  - 115,831 kWhe/year
  - 15,117 euros/year, no electricity tax
  - 12,671 euros/year, electricity tax is paid
- Years 6–10:
  - 104,248 kWhe/year
  - 13,606 euros/year, no electricity tax
  - 11,404 euros/year, electricity tax is paid
- Years 11–25:
  - 92,664 kWhe/year
  - 12,094 euros/year, no electricity tax
  - 10,137 euros/year, electricity tax is paid
- Years 26–30:
  - 81,081 kWhe/year
  - 10,582 euros/year, no electricity tax
  - 8870 euros/year, electricity tax is paid

Capital investment appraisal can be done in many ways. The following methods are used here.

The equivalent annuity method expresses the net present value (NPV) as an annualized cash flow by dividing it by the present value of the annuity factor. Capital investment appraisals done using equivalent annuity usually compare projects with different life spans.

The net present value (NPV) of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values of the individual cash flows of the same entity.

Payback period refers to the period of time required to recoup the funds expended in an investment, or to reach the break-even point.

The profitability of the photovoltaic investment, when electricity tax is not paid:

- The equivalent annuity method
  - Annuity: 9586 euros
  - Average annual net revenue: 11,698 euros
  - Because the equivalent annuity is smaller than the average annual net revenue, the investment is profitable.
- Net present value (NPV)
  - The sum of the present values of the individual cash flows: 40,781 euros
  - Internal rate of return: 8 %
  - The sum of the present values of the individual cash flows is positive and the internal rate of return is higher than the discount rate. Hence, the investment is profitable.
- The payback period
  - The payback period is 12.7 years.

The profitability of the photovoltaic investment, when electricity tax is paid:

- The equivalent annuity method
  - Equivalent annuity: 9586 euros
  - Average annual net revenue: 9647 euros
  - Because the equivalent annuity is smaller than the average annual net revenue, the investment is profitable.
- Net present value (NPV)
  - The sum of the present values of the individual cash flows: 8065 euros
  - Internal rate of return: 6 %
  - The sum of the present values of the individual cash flows is positive and the internal rate of return is higher than the discount rate. Hence, the investment is profitable.
- The payback period
  - The payback period is 15.4 years.

The real cost of electricity

The market price of electricity is very much time and location dependent. The costs of generating electricity depend on electricity source, time and location. Typically the cost of electricity is calculated by summing up the fuel, capital and operating costs.

In the European Union, there is an Emission Trading System that has been in place for carbon dioxide emissions since 2005. The price for a ton of carbon dioxide emitted has remained very low and has been only a fraction of the real environmental and social costs. There has been no attempt for similar emission trading system for other emissions, such as sulphur or nitrous oxides. These costs have shifted to fuel, capital and operating costs by legislation and emission limits.

In this report, the hidden costs of electricity generation for different electricity generation methods and mixes have been appraised by adding the unit costs of certain emissions and other environmental burdens to the life cycle analysis tool. Government subsidies – such as feed-in-tariffs, tax exemptions and investment subsidies – have not been included as hidden costs. Also the governments' decades long R&D support, which totals worldwide trillions of euros, has not been included. In this report, all the emissions and environmental damages have not been counted, hence the estimated hidden costs are probably conservative.

For nuclear power, the hidden costs in this report include the costs of nuclear waste after the closure of the waste repository. These long-time costs are very difficult to appraise because of the huge time scale of up to a million years. The operating costs include the estimated costs of nuclear waste during the first 150 years[16]. The costs during the period of 150 years to one million years are simply assumed to be the same as the costs during the first 150 years.

Another hidden cost of nuclear electricity is related to the liability and insurance problem. In the United States, the Price-Anderson Act enacted into law in 1957, limits the industry's liability in case of a catastrophic accident. No insurance company in the world would insure a nuclear plant or provide home or business-owners insurance to cover nuclear hazards. This is why similar acts have been adopted in each nuclear power country. The tax payers get cheaper electricity, but they pay the bill in case of a nuclear catastrophe. It has been estimated that with

[16] Yucca Mountain cost jumps sharply, Chemical & Engineering News, August 11, 2008.

the current about 400 reactors there is a major nuclear accident once every 25 years (1986 Tshernobyl, 2011 Fukushima)[17].

A conservative estimate of hidden costs in nuclear power is 0.012 euro/kWh_e. In 2004, Kammen and Pacca[18] estimated that the conservative hidden costs of nuclear power in the United States (excluding nuclear waste and public R&D costs) are 0.009 dollar/kWh_e.

The environmental and social cost of carbon dioxide has been estimated to be at least 30 euro/kWh_e[19], which is the lower limit of the costs. Other emissions that have been used in the hidden costs appraisal are $SO2_e$, $PO4_e$, NO_x, fine particulates and volatile organic compounds (VOCs). The impacts of these emissions are more local than for carbon dioxide emissions and the emissions affect more in the densely populated areas. Hence the unit costs per ton of emissions are about ten times higher in Central Europe than in Finland. In this report (also for world electricity mix), the unit costs specifically for Finland have been used[20]. Eutrophication costs data is from United States[21].

[17] Rabl Ari, Rabl Veronika A., External costs of nuclear: Greater or less than the alternatives?, Energy Policy, vol. 57, 575 –584, 2013.

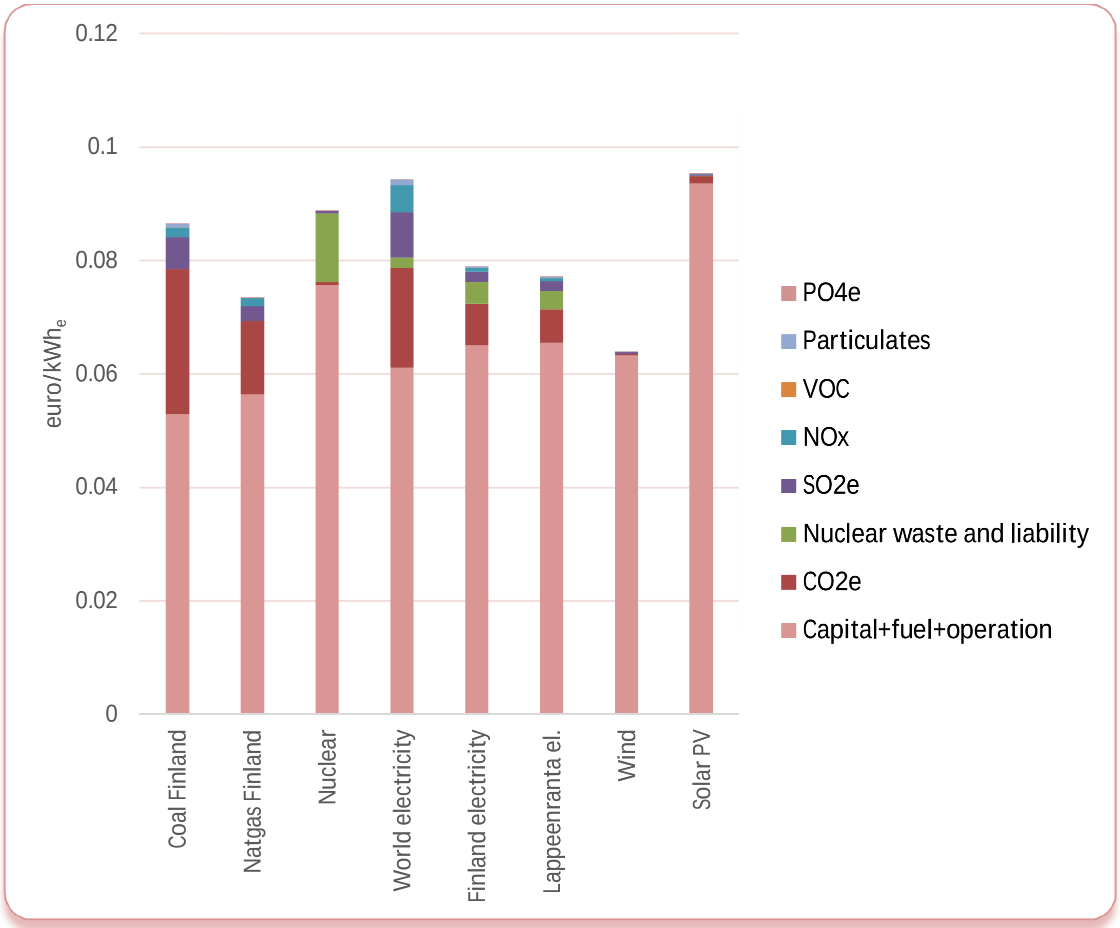
[18] Kammen D.M., Pacca S., Assessing the costs of electricity, Annu. Rev. Environ. Resour., vol. 29, 301–344, 2004.

[19] Howard P.H., Omitted damages: What’s missing from the social cost of carbon, The Cost of Carbon Pollution Project, 2014.

[20] Holland Mike, Pye Steve, Watkiss Paul, Droste-Franke Bert, Bickel Peter, Damages per tonne emission of $PM_{2.5}$, NH_3, SO_2, NO_x and VOCs from each EU25 Member State (excludin Cyprus) and surrounding seas, AEA Technology Environment, 2005.

[21] Roberts Bronte Marie, Development of portable recycled vertical flow constructed wetlands for the sustainable treatment of domestic greywater and dairy wastewater, Master of Science thesis, Department of Animal Sciences, Colorado State University, 2011.

The electricity generation costs (fuel, capital and operating costs) are from international data[22]. For photovoltaic electricity, the electricity generation costs are from this report.



Electricity generation costs for different electricity generation methods and mixes per kWhe. Typically, only capital, fuel and operating costs are counted, when the cost of electricity is reported. All the other costs are hidden costs that are generally excluded when comparing the electricity generation costs. If the investment subsidy of 30% is taken into account in case of Solar PV, the cost of photovoltaic electricity would be 0.071 euro/kWhe.

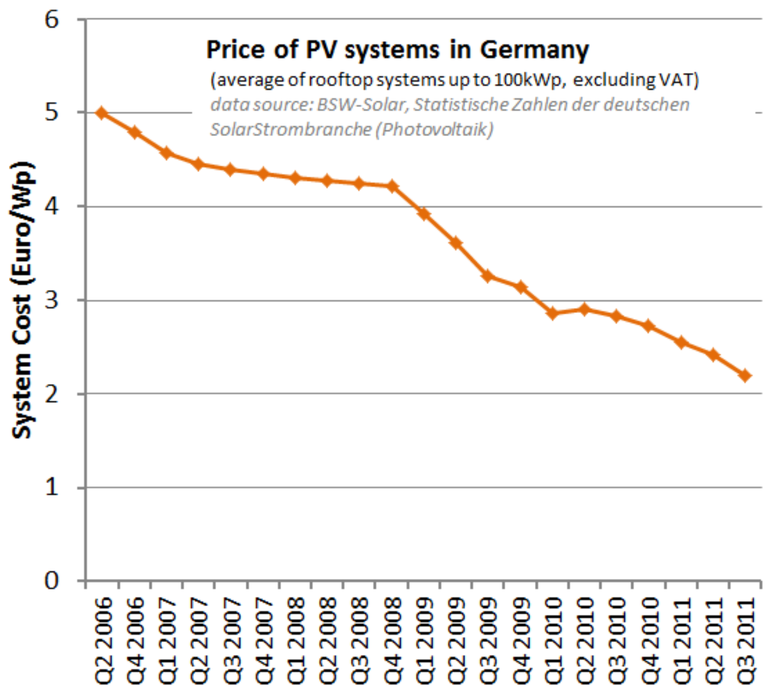
[22] Levelized cost of new generation resources in the Annual Energy Outlook 2013, U.S. Energy Information Administration, 2013.

Conclusions

The life-cycle environmental impacts of the Huhtiniemi rooftop photovoltaic system compared to Lappeenrannan Energia grid electricity are positive. For example, the greenhouse gas emissions would be 383 tonnes CO_2e lower and the creation of high-level radioactive waste would be 94% lower.

The cost of the Huhtiniemi photovoltaic system without investment subsidy is estimated to be 1.37 euros/Wp (2014). In Germany, the cost of smaller photovoltaic systems in the end of 2011 was about 2 euros/kWp, and the costs were plummeting.

The cost of photovoltaic panels is predicted to come down also in coming years. On the other hand, when prices go down, it is obvious that the tax credits and investment subsidies will be cut off. Thus, waiting for even smaller prices of photovoltaic panels does not necessarily pay off.



The rooftop photovoltaic system cost per nominal power in Germany[23].

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The following reference data have been used in the analysis. The data have been updated, if it has been outdated.

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Uncertainties in life-cycle analysis

Generally the reliability of the results from a life-cycle analysis depends on the accuracy and reliability of the calculation models and data banks.

In practice, every case is a special case. The feed data and consequently the results are dependent on time, location, raw material, company, political decisions, legislation etc. These factors can be taken into account by changing models and inventory parameters. However, in practice for example country-dependent average models and parameters are used.

For example, crude oil is produced in thousands of locations globally, and the quality of oil differs widely. Good-quality light oil from an easy well can be pumped, transported and refined easily, while bituminous oil requires much more severe processing. Consequently the well-to-fuel emissions are higher in the latter case.

In the future, oil and other raw materials must be extracted from more difficult reserves and the emissions will grow. On the other hand, more efficient production methods may lower the environmental impacts. Political decisions, such as lower sulphur content limits in fuels and exhaust gases and the ban of CFC compounds, have also an effect on emissions.

Some actions that are intended to decrease certain emissions may have contradictory effects on other emissions. For example, flue-gas desulphurization and electrostatic precipitators decrease the emissions of sulphur dioxide and particulates, but at the same time more energy is used and carbon dioxide emissions increase.