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Greenhouse Gas Emissions Inventory for Photovoltaic and Wind Systems in Switzerland

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Presented by R. Dones at IAEA Advisory Group Meeting on

Assessment of Greenhouse Gas Emissions from the Full Energy Chain of Solar and Wind Power

Vienna, 21-24 October 1996

Content

- ⇒ Overview of the Swiss Study
- ⇒ Photovoltaic Full Energy Chain
- ⇒ Wind Full Energy Chain
- ⇒ Comparisons with Present European Electricity Generating Systems
- ⇒ Comparisons with Future Photovoltaic Systems

Swiss Studies on Life-Cycle Analysis of Energy Systems

Co-operation:

- Swiss Federal Institute of Technology (ETHZ),
  Institute of Energy Technology,
  Energy, Materials, Environment Group:
  Fossil systems & Renewables
- Paul Scherrer Institute (PSI),
  Department of Nuclear Energy and Safety Research,
  Systems/Safety Analysis Section:
  Coal & Nuclear systems

Assessment of full energy chains of current (1994) Swiss and UCPTE[1] electricity and heating systems:

Ökoinventare von Energiesystemen [2]
3rd Ed., Zurich (to be published 1996)

Future electricity systems have been assessed in:

Environmental Inventories for Future Electricity Supply Systems for Switzerland [3]

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[1] Union for the Co-ordination of Production and Transmission of Electricity

[2] Frischknecht et al., "Ökoinventare von Energiesystemen — Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz", 3rd Ed., ETHZ/PSI, Zurich, to be published 1996 (1st edition 1994).

[3] Dones R., Gantner U., Hirschberg S., (PSI), and Doka G., Knoepfel I. (ETHZ), "Environmental Inventories for Future Electricity Supply Systems for Switzerland", PSI Report No.96-07, Würenlingen and Villigen, CH (1996).

Methodology used for LCA Studies

- Entire Lifetime of plants included (construction, operation, decommissioning)
- Material production, transportation, and downstream processes included
- Full Energy Chains examined (Cradle to Grave) and each Step analysed separately (Process chain analysis)
- Allocation criteria developed for multi-output processes
- ~ 300 air & water pollutants & solid wastes; ≈ 1000 processes considered

Tools

- Database developed by ETHZ (ECOINVENT)
- Set of linear equations solved with Gauss-Jordan Algorithm

Greenhouse Gases Warming Potentials

IPCC (1996) GWP_{100} used for this assessment

GWP_{100}	IPCC 1994	IPCC 1996
CH_4	24.5	21
N_2O	320	310
CF_4	6300	6500
HFC-134a	1300	1300

PV plants assessed in the study

3 kWp, m-Si and p-Si cells

Two basic applications were analysed:

- Building-integrated panels (laminate)
- Self-standing panels placed on buildings

Three types of installation were considered

- Façade
- Flat roof
- Slanted roof

Large plants

- PHALK 500, m-Si cells
- SSW 100, p-Si cells

Overview

The analysis is the result of extensive work performed at ETHZ.

Hagedorn (1992, Munchen) considered for his assessment the cumulated energy flows of processes and services for the production of monocrystalline (m), polycrystalline (p) and amorphous (a) cells.

The Swiss inventory (for m-Si and p-Si) takes into account also the material flows for the production of all materials and energy carriers involved throughout the full process chain.

The chain was decomposed into:

- Metallurgical grade (MG) silicon manufacture
- m-Si (p-Si) wafer manufacture (including electronic grade (EG) Si production)
- m-Si (p-Si) cell fabrication
- m-Si (p-Si) laminate/panel fabrication
- Installation (including support, inverter and other electrical components)
- Operation

For the m-Si cells, the panels used as reference are produced by Arco (USA)

For the p-Si cells, the panels used as reference are produced by Kyocera (Japan)

Some key assumptions for the assessment (1)

- Energy requirement for the production of EG Silicon = 129 kWh/kg (Linton, 1993)

- m-Si Wafer 98 cm^2; thickness = 300 μm (450 μm in Hagedorn); cut thickness = 200 μm (450 μm in Hagedorn);

  MG Si requirement is ~ 67 g/wafer, EG Si requirement is ~ 12 g/wafer (estimations from thicknesses); total electricity need for EG Si manufacture = ~ 1.57 kWh/wafer;

  factor ~ 0.56 reduction from Hagedorn for total electricity need for wafer fabrication = ~ 1.57 kWh/wafer

- p-Si Wafer 107 cm^2; thickness = 300 μm (350 μm in Hagedorn); cut thickness = 200 μm;

  MG Si requirement is ~ 129 g/wafer (factor 0.9 reduction from Hagedorn ~ 141 g/wafer); estimated EG Si is ~ 24 g/wafer;

  same reduction for total electricity need for wafer fabrication = ~ 1.56 kWh/wafer to add to EG Si manufacture = ~ 3.06 kWh/wafer

Some key assumptions for the assessment (2)

- Electricity requirement for m-Si cell = ~ 1.3 kWh/cell (Hagedorn)
- Electricity requirement for p-Si cell = ~ 1.3 kWh/cell (Linton)
- Nominal power: m-Si cell = 1.62 W_p; and p-Si cell = 1.5 W_p
- Cell efficiency: m-Si = 16.5%; p-Si = 14%
- Assumed average yield for panels per kW_p in Switzerland = 860 kWh/a*kW_p

Site in Switzerland	Yield kWh/a*kW_p
Middle Lands (foggy areas)	520-700
Middle Lands (good areas)	700-880
South and Pre Alps	790-1140
Alps	1230-1760

Source: Frischknecht et al., 1994

- Lifetime of the panels = 30 years
- No back-up system considered

Large PV plants in Switzerland

PHALK 500

Photovoltaisches Alpines Kraftwerk

- Site: Mont Soleil, Jura, 1270 m altitude
- Construction year 1992
- Nominal power: 560 kW_p
- ~ 1200 kWh/kW_p, ~ 680 MWh/a (2.44 TJ/a)
- 10,560 m-Si, 53 W_p lam. (Siemens Solar, Munich) 36 cells/lam. (Arco Solar Inc., California)
- 110 steel supports

SSW 100

- Site: on guard-rail (Schallschutzwand) in the highway N13 (GR)
- Construction year 1989
- Nominal power: 110 kW_p
- ~ 1000 kWh/kW_p, ~ 110 MWh/a (0.396 TJ/a)
- 2,208 p-Si, 50 W_p lam. (Kyocera, Japan), grouped by 12
- 930 m long

Construction materials for the PHALK plant

Material	Mass (kg)
Aluminium (0% recycled)	313
Aluminium (100% rec.)	158
Chemicals	220
Concrete	288,000
Copper	13,270
Glass	33
Lead	60
Mineral wool	1,342
MG Silicon	219
PE (HD)	215
PE (LD)	4,038
PUR	455
PVC	80
Steel (high alloyed)	177,800
Steel (low alloyed)	11,652
Steel (unalloyed)	7,690
Zinc	12,511
m-Si laminates (36 cells)	10560 units

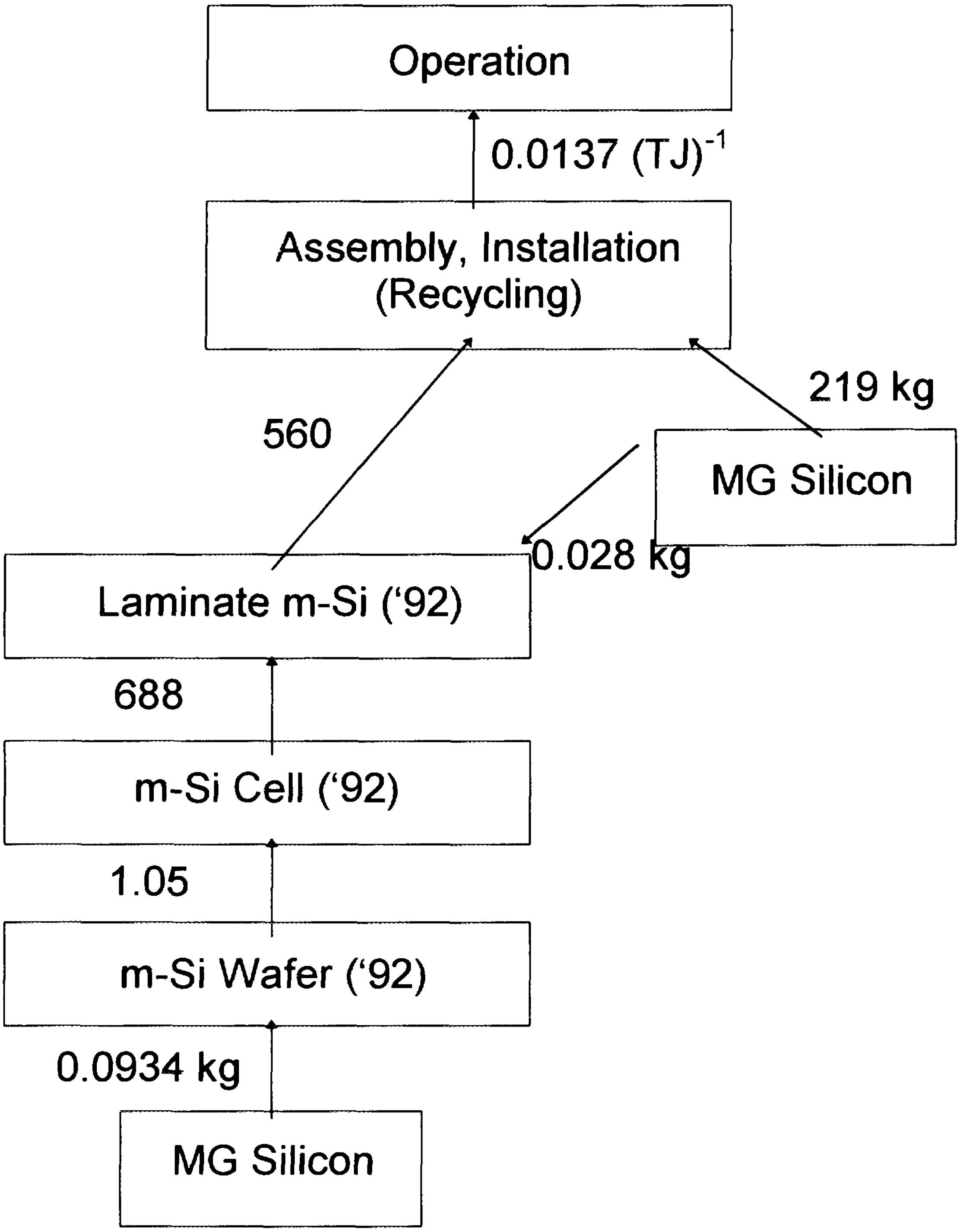
Source: Frischknecht et al., 1994

Construction materials for the SSW plant

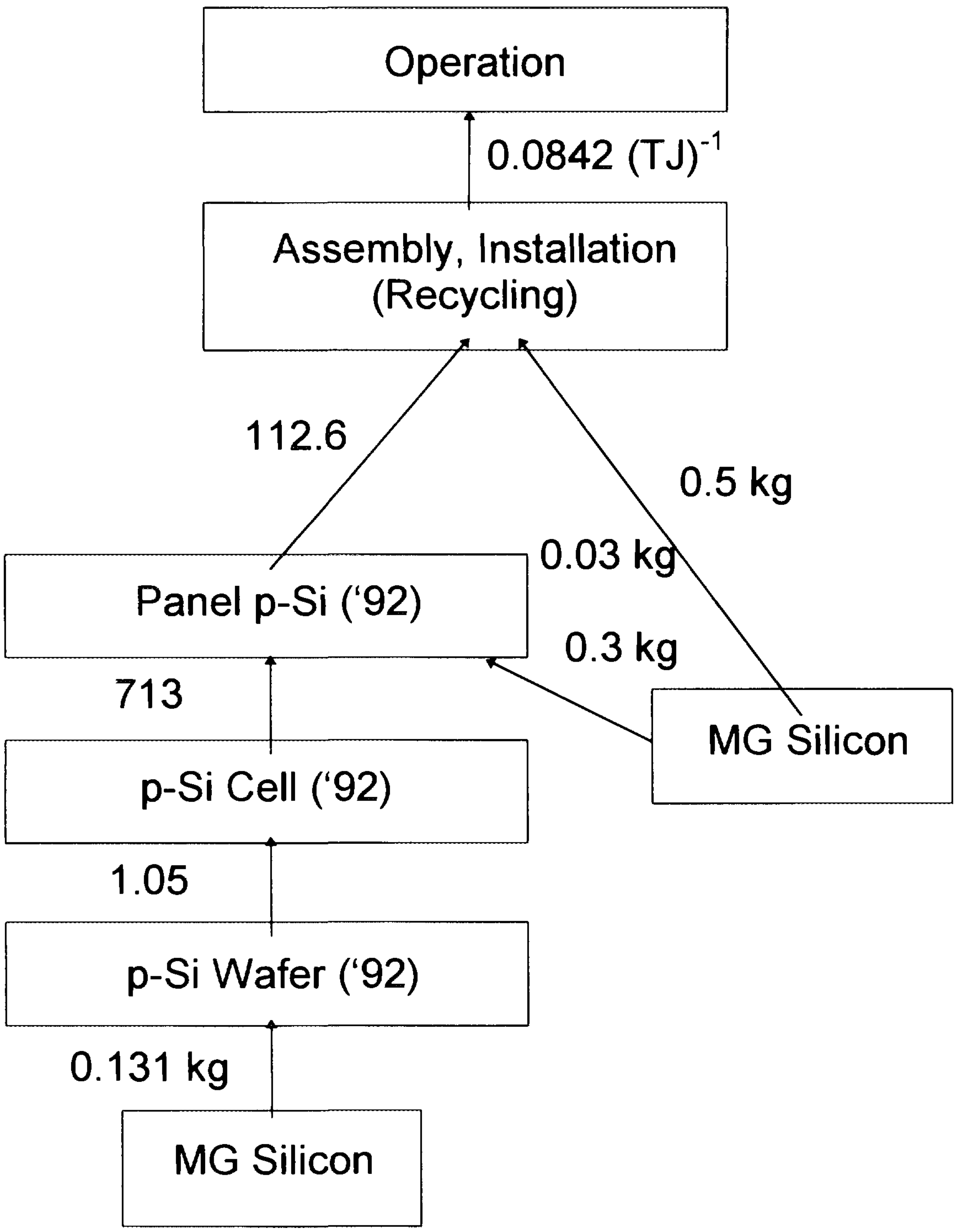
Material	Mass (kg)
Aluminium (0% recycled)	383
Ceramics	129
Concrete	86,000
Copper	5,070
Mineral wool	121
EG Silicon	0.5
PE (LD)	3,606
PVC	110
Steel (high alloyed)	1366
Steel (low alloyed)	24,400
Steel (unalloyed)	16,620
Zinc	1,150
p-Si panels	2,208 units

Source: Frischknecht et al., 1994

PHALK 500 Plant



SSW 100 kWp Plant



Future Photovoltaic Systems

- Two systems have been considered based on:
  - Monocrystalline silicon cells
  - Amorphous silicon cells

- Inventory based on available technology — no revolutionary innovations considered:
  - today's MG silicon production techniques;
  - higher gain for silicon purification (20% → 78%) & reduced process energy (by 40%);
  - process energy for m-Si wafer production ≈8 times lower;
  - 20% lower electricity needs for m-Si cell manufacture;
  - process electricity for panel manufacture reduced by a factor of approx. 4;
  - total direct electricity need for one m-Si panel is approx. 1160 kWh/kW_{peak};
  - total direct electricity need for one a-Si panel is approx. 350 kWh/kW_{peak};
  - approx. 40 kg CO_2 are directly emitted in a-Si panel production (scrubbing with methane);

- Efficiency increases: 15% → 18% for m-Si, 5% → 10% for a-Si

- Load factor 10% (Swiss conditions in the lowlands, corresponding to 880 kWh/kW_{peak}), 30 years lifetime
  Only 3 kW_{peak} slanted roof panel plants considered

Results for Current PV Systems in Switzerland

⇒ GHGs mostly originate from the manufacturing of cells (MG Si + wafer + cell fabrication), typically 70-80% of total for panels

⇒ Wafer manufacture contributes typically 40-50% to total GHG emissions in the case of panels

⇒ For large plants, wafer manufacture and the assembly/installation are the largest contributors (the latter, up to 50% of total)

⇒ GHGs mostly originate from electricity requirements (on the order of ~ 80%)

⇒ CO_2 emissions contribute 87-93%

⇒ CF_4 (from Al production) contribute 1-3% for panels,
5-7% for plants

⇒ CFCs contribute < 1%

⇒ Building-integrated panels have 5-15% less associated GHG emissions than non-integrated ones

⇒ Results are directly proportional to the yield, therefore are strongly site specific

Wind Energy Converters in Switzerland

- Seven operational horizontal-axis wind turbines are connected to the net:

• Grenchenberg	150 kW
• Chürstein (Appenzell)	80
• Simplon	30
• Sool (Jura)	30
• Wyssacher (Emmental)	10
• Sursee	5
• Winterthur	3
Total	308 kW

- 50 other non-connected small plants exist
- Technical potential: ≈ 1000 GWh/a

Swiss Plants considered in the study

- Simplon (directly modelled)
- Grenchenberg (extrapolated)
- Sool (extrapolated)

Overview of the analysed Plants

		Simplon	Sool	Grenchenberg
Nominal power	kW	30	30	150
Tower height	m	22	18	30
Rotor diameter	m	12.5	12.5	23.8
Blades		2	2	3
Start operation	year	1990	1986	1994
Average output	kWh/a	20864	14868	99964
Availability	%	99	94	96

Key assumptions for the analysis

- Lifetime: mobile parts 20 years[1]
  structural parts 50 years[1]
- No back-up systems considered[2]

[1] [Hagedorn et al., 1991]

[2]Source: Frischknecht et al. 1996

Characteristics of the Simplon Plant

General	Wind speed range	4 - 20 m/s
	Nominal wind speed	7 / 11.4 m/s
	Rated power	8.5 / 30 kW
Rotor	Diameter	12.5 m
	Blades	2
	Nominal rotational speed	46 / 92 rpm
	Position relative to tower	leeward
	Hub height	22.4 m
Blade	Length	6100 mm
	Thickness	420 mm
	Material	Fiber reinforced Epoxy
	Weight	73 kg
Orientation		Passive
Generator		Asynchronous
	Nominal Voltage/Frequency	380 V / 50 Hz
Tower	Type	conical, hollow octagonal cr.sect.
	Material	8 mm hot-galvanised sheet-steel
	Height	22 m

Source: Frischknecht et al., 1996

Simplon Plant Construction Material Requirements

Component	Material	Mass (kg)
Tower	Steel (unalloyed)	5285
	Hartlot w/o Cd	14
	Paint	37
Basement	Steel (unalloyed)	2367
	Cement	7415
	Sand & gravel	40850
	Explosives	10
Rotor	Glass	87.6
	Polyethylene (high density)	58.4
Nacelle & Electrical parts	Aluminium (0% recycled)	12
	Aluminium (100% rec.)	3
	Cast iron	268
	Copper	245
	Glass	36
	Rubber	~3.2
	Lead	~0.2
	Nickel	~0.1
	Platinum	~0.0003
	Polyethylene (high density)	219
	Polypropylene	20
	PVC	158
	Steel (unalloyed)	343
	Steel (low alloyed)	556
	Tin	~0.5
	Zinc	~0.07

Source: Frischknecht et al., 1996

Simplon Plant Energy & Service Requirements for Construction and Operation

Component	Energy carrier / Service	Amount
Tower	Transport road	7930 tkm
	Fuel oil in 1 MW boiler	8300 kWh_{th}
	Natural gas in >100 kW boiler	8300 kWh_{th}
	Electricity UCPTE (med. volt.)	610 kWh_e
Basement	Transport road	1080 tkm
	Transport rail	2160 tkm
	Fuel oil in 1 MW boiler	3700 kWh_{th}
	Natural gas in >100 kW boiler	3700 kWh_{th}
	Electricity UCPTE (med. volt.)	270 kWh_e
Installation	Transport road	1600 tkm
		400 person*km
	Diesel in construction machinery	1400 kWh_{th}
Rotor	Transport road	15 tkm
	Transport rail	64 tkm
Nacelle & Electrical parts	Transport road	2061 tkm
	Transport rail	389 tkm
	Fuel oil in 1 MW boiler	3450 kWh_{th}
	Natural gas in >100 kW boiler	3450 kWh_{th}
	Electricity UCPTE (med. volt.)	250 kWh_e
Operation	*Transport road*	*160 person*km*
	Fuel oil, regional supply	*84 kg*

Source: Frischknecht et al., 1996

Results for Wind Power Plants in Switzerland

Wind Plants	$g(CO_2\text{-eq.})/kWh$
Grenchenberg 150 kW	28
Simplon 30 kW	52
Sool 30 kW	65
Mix	36

⇒ GHGs mostly originate (~70%) from materials:

- Steel and Iron 40%
- Concrete 14%
- Plastics 8%
- Copper 6%

⇒ Second contributors are fossil fuels (~20%)

⇒ CO_2 emissions contribute ~ 93%

⇒ Results are strongly site specific

⇒ Lower total emission for greater installed power

- Total material requirement (average plant): 0.4 kg/kWh
  (half is gravel)
- Total energy carriers requirement: 0.1-0.22 kWh/kWh_e

Comparison of Selected Present and Future Electricity Systems

GHG Emissions from Full Chain g(CO_2-equiv.)/kWh (IPCC,1996)		Present average UCPTE/CH*	Future (2020-2030) Switzerland**
Lignite	average plant	1340	na
Hard Coal	PC* (*PC/PFBC***)	1071	*760*
Oil	average plant	855	na
	CC	na	549
Gas	average plant, gas mix	915	na
	CC, natural gas	na	389
Nuclear	LWRs once-through chain	16-18 [b] (14-16) [c] (7) [d]	6
Hydro	Dam & run-of-river	4	4
Wind [e]	average plant	36	na
Photovoltaic [e]	Large plants	171-235 [f]	na
	3kWp m-Si	114-180	44
	3kWp p-Si	189-277	na
	3kWp a-Si	na	27

a It represents present technology b UCPTEand CH, respectively.
c In brackets the values w/o CFCs
d Calculated for CH PWRs with centrifuge enrichment only
e Swiss average conditions only
f PHALK 500 kW (m-Si), SSW 100 kW_p (p-Si), respectively, reference year for panels 1992

Sources: * Frischknecht et al., 1994, 1996
** Dones et al., 1996

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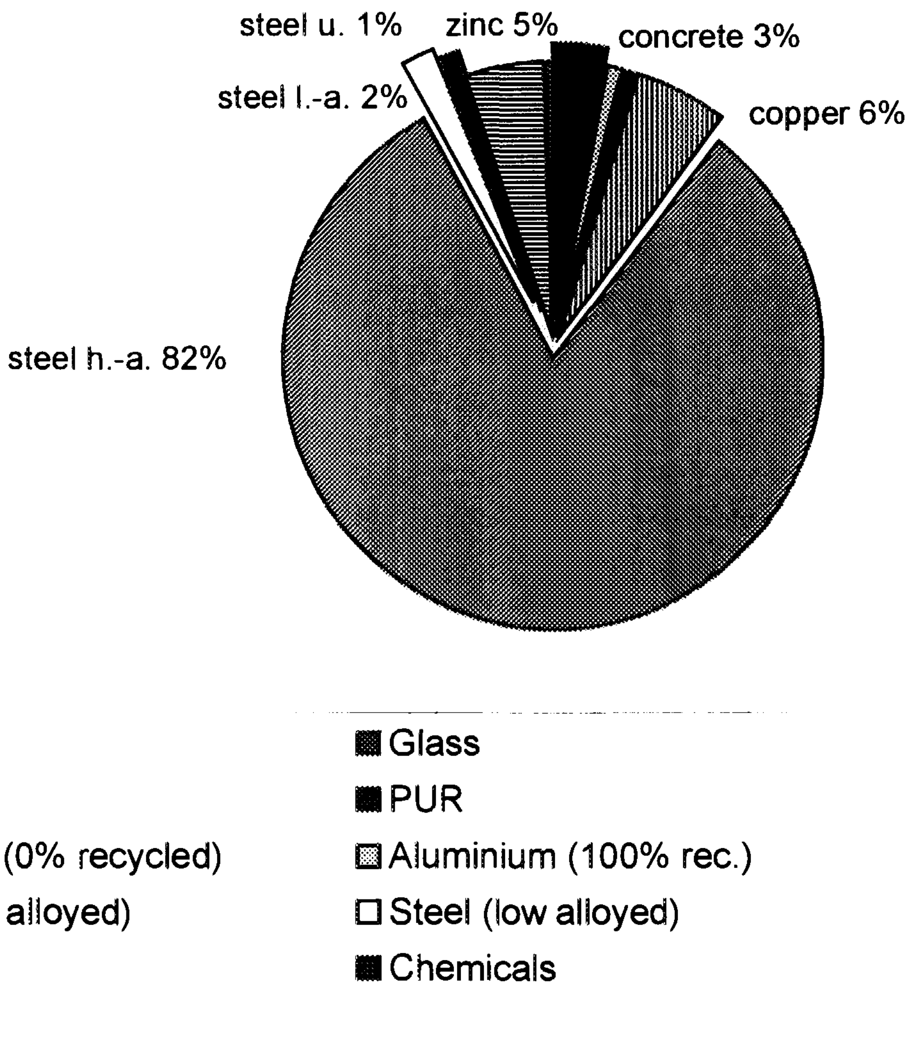
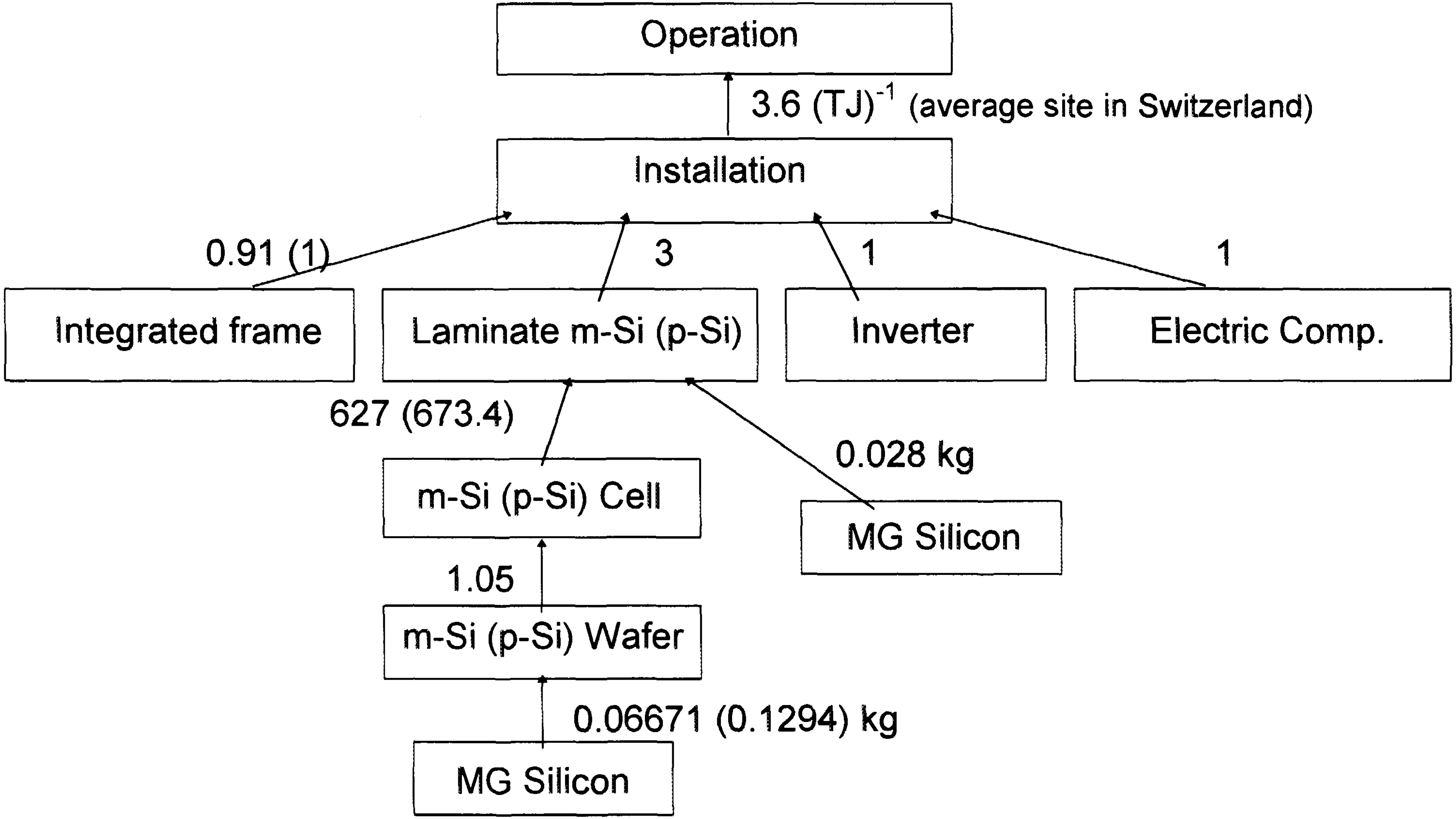
GHGs associated with construction materials for the PHALK plant

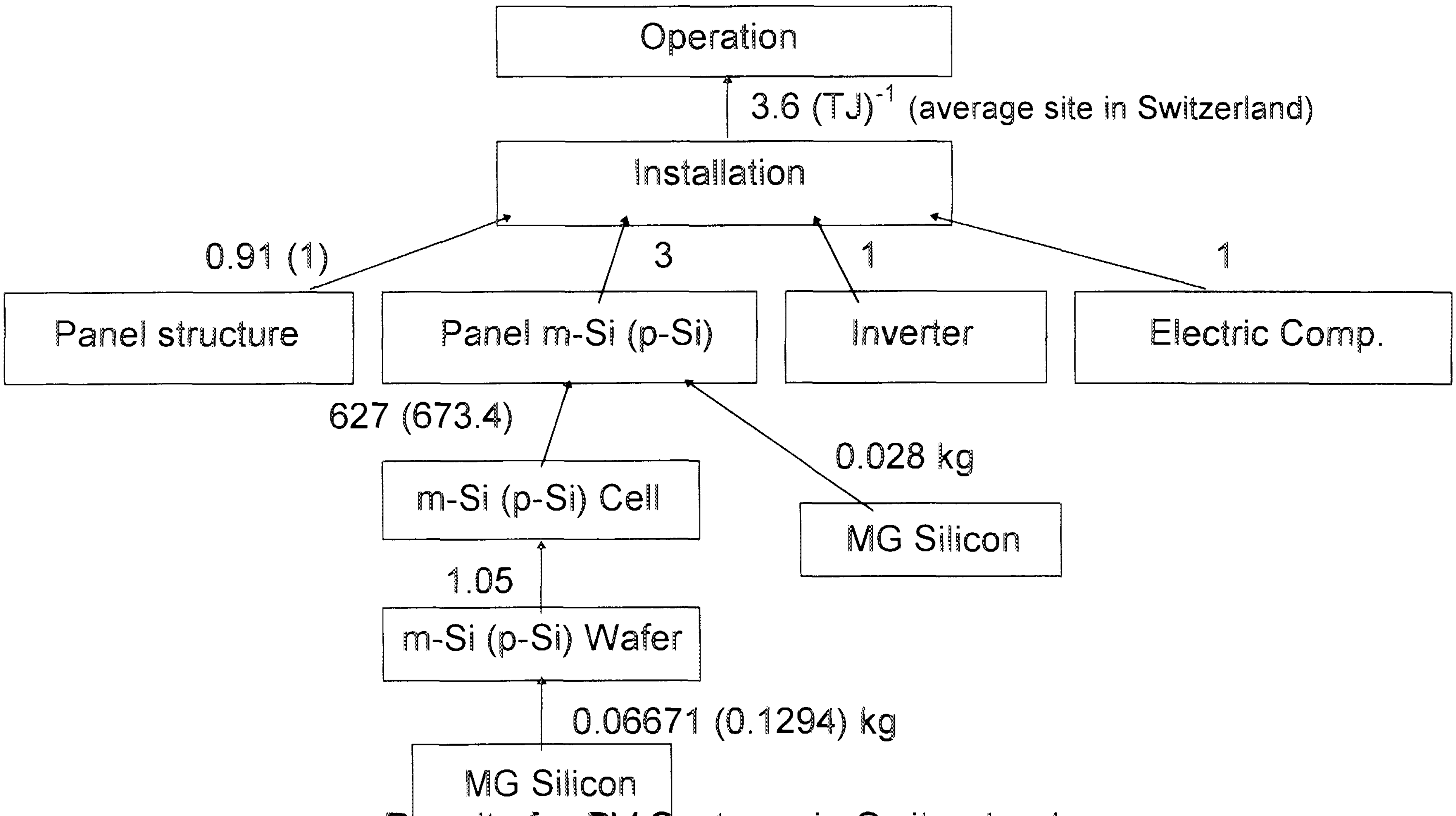


After Frischknecht et al., 1994

3kWp m-Si (p-Si) Slanted Roof Integrated PV Plant



3kWp m-Si (p-Si) Slanted Roof Panel



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Type	Cell	Installation	g(CO_2-eq.)/kWh
3 kWp panels	m-Si	Façade, integrated	154
		Façade, panel	180
		Flat roof, panel	132
		Slanted roof, integrated	114
		Slanted roof, panel	127
	p-Si	Façade, integrated	260
		Façade, panel	277
		Flat roof, panel	202
		Slanted roof, integrated	189
		Slanted roof, panel	196
large plants	m-Si	PHALK 500	171
	p-Si	SSW 100	235

Sources: Frischknecht et al., 1994, 1996

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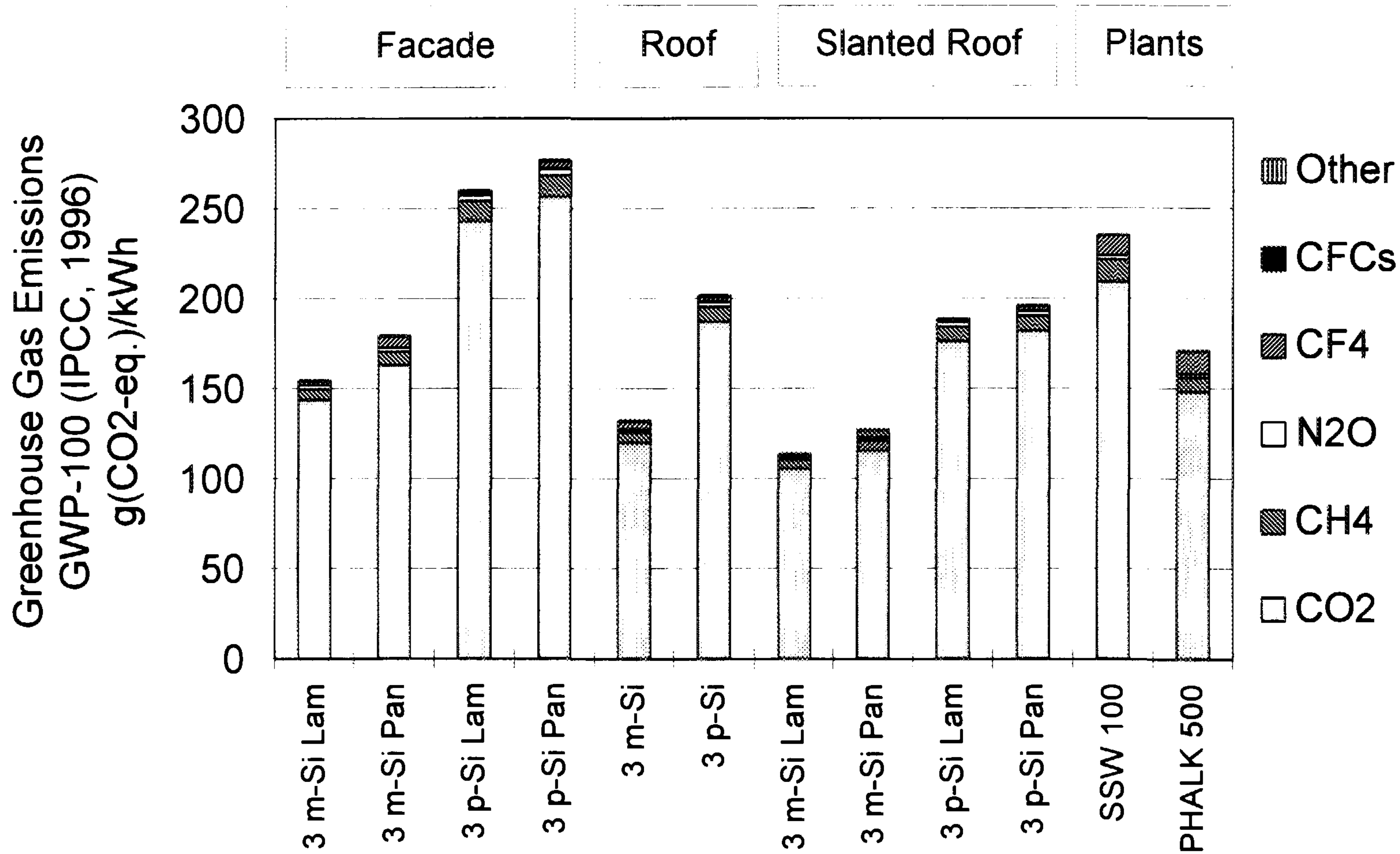
Contributions by Species (absolute values) to total GHG Emission associated with PV Panels and Plants in Switzerland



Source: Frischknecht et al., 1994, 1996

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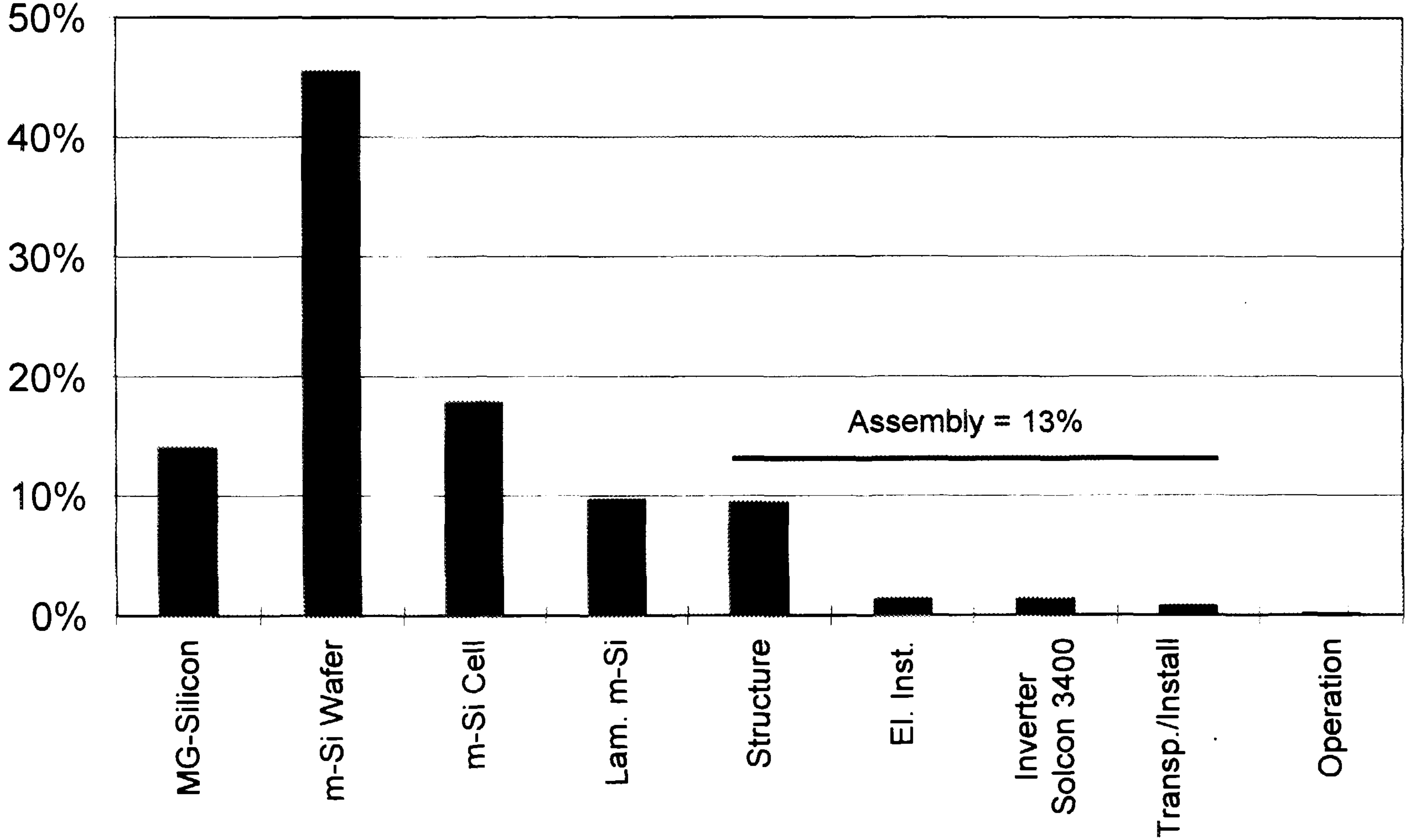
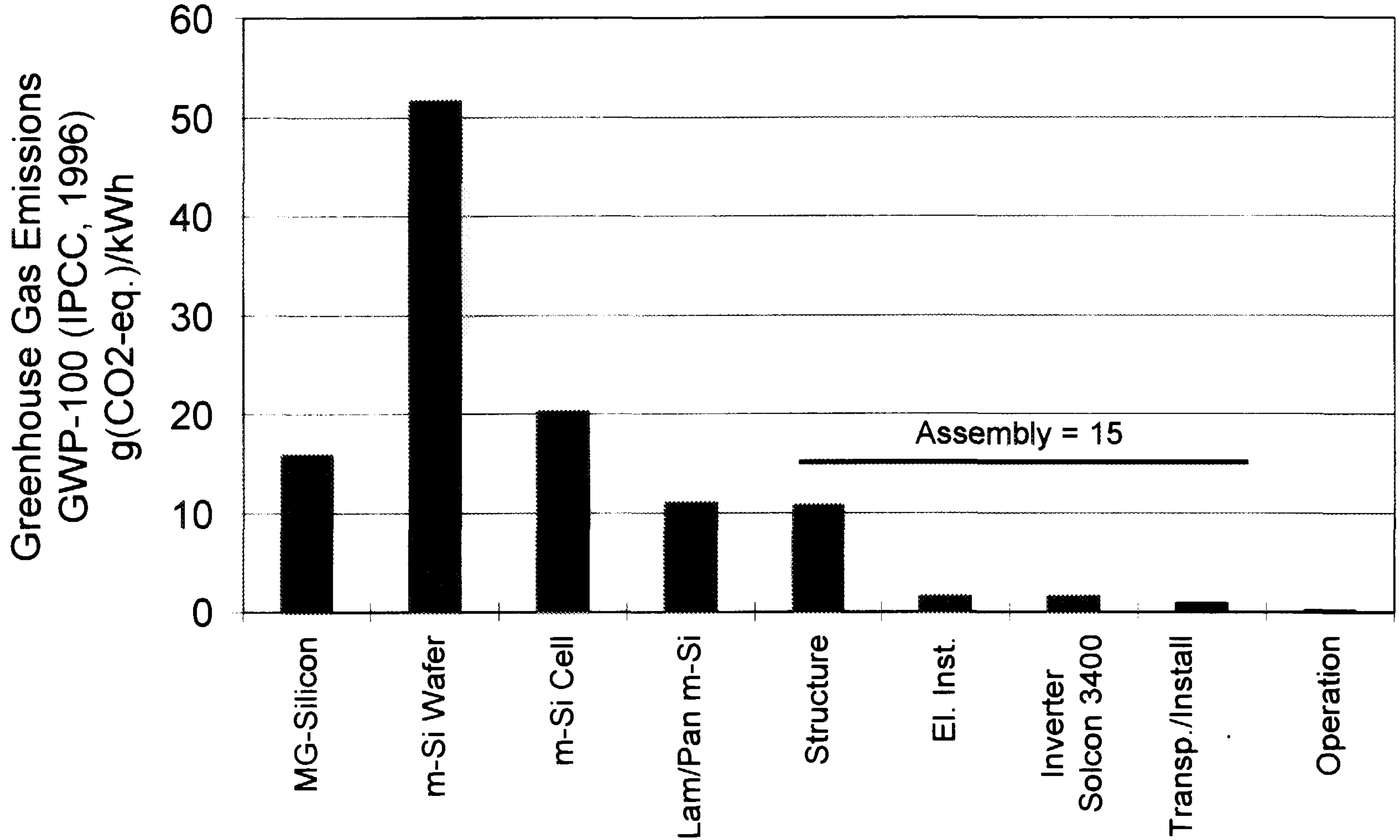
Relative Contributions from the Steps of PV chain to total GHG Emission associated with m-Si Slanted-Roof Integrated Panels



Source: Frischknecht et al., 1996

Contributions from the Steps of PV chain to total GHGs associated with m-Si Slanted-Roof Integrated Panels



Source: Frischknecht et al., 1996

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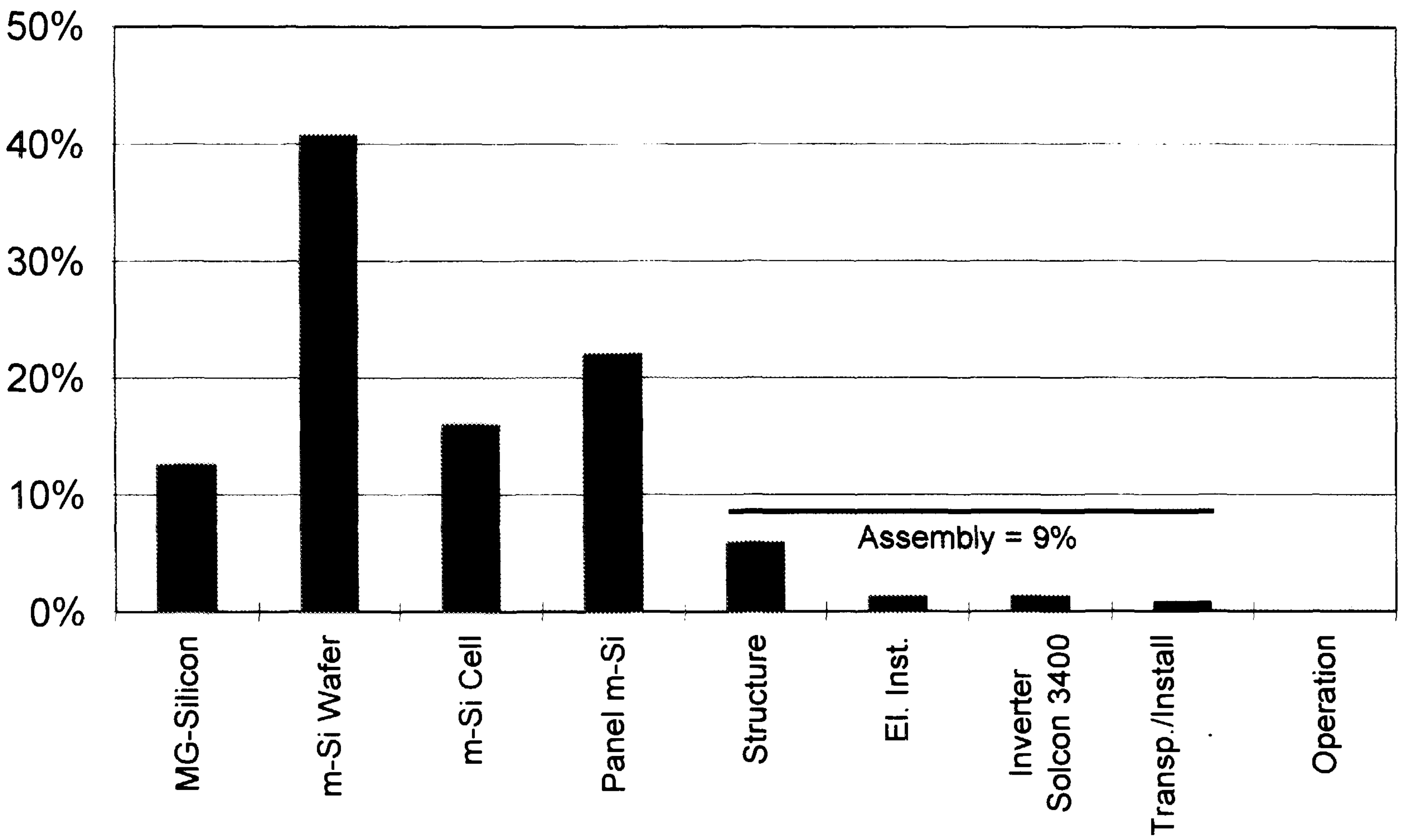
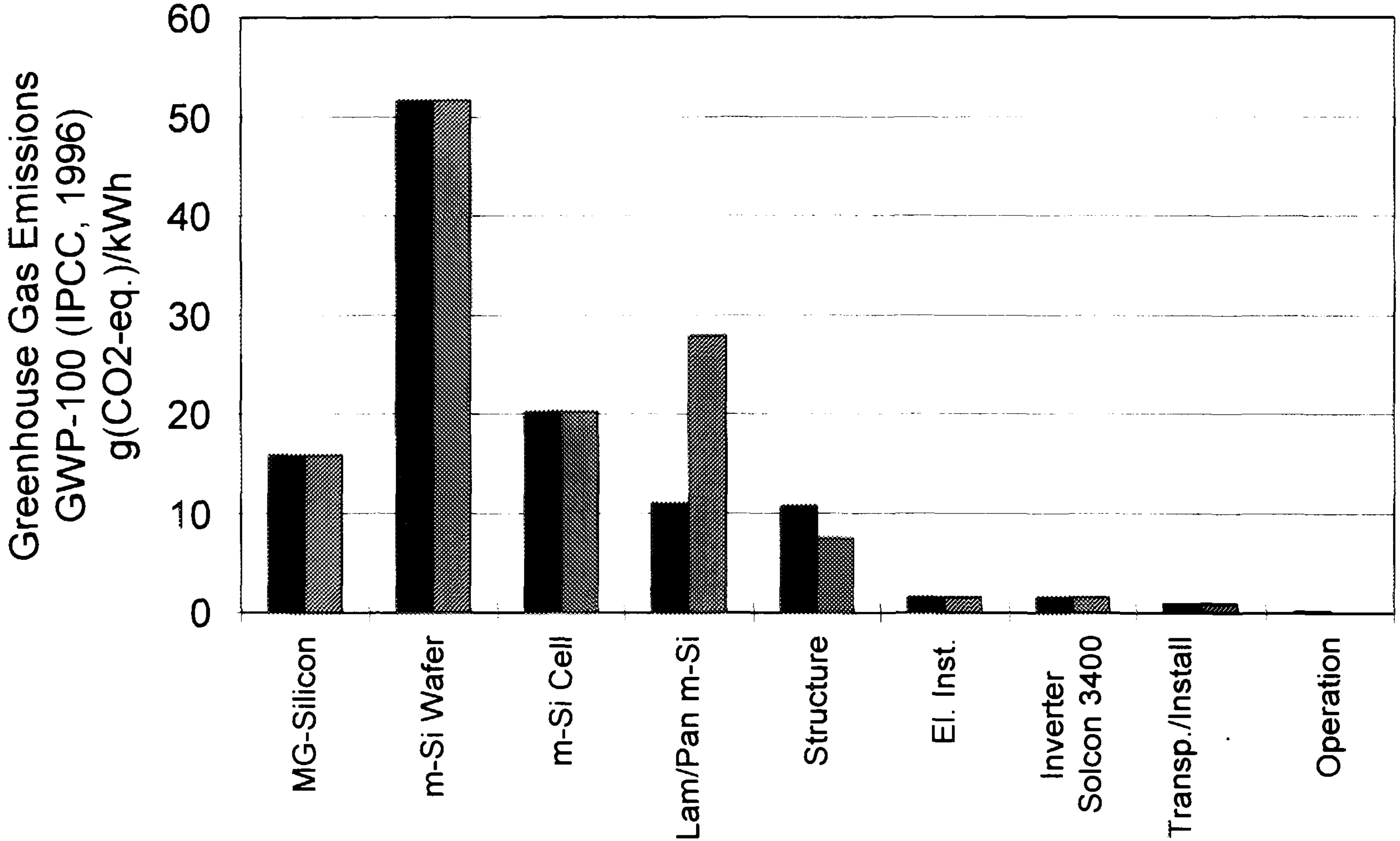
Relative Contributions from the Steps of PV chain to total GHG Emission associated with m-Si Slanted-Roof Panels



Source: Frischknecht et al.. 1996

Contributions from the steps of PV chain to total GHGs associated with m-Si Slanted-Roof Integrated *(left)* and Non-integrated Panels *(right)*



Source: Frischknecht et al., 1996

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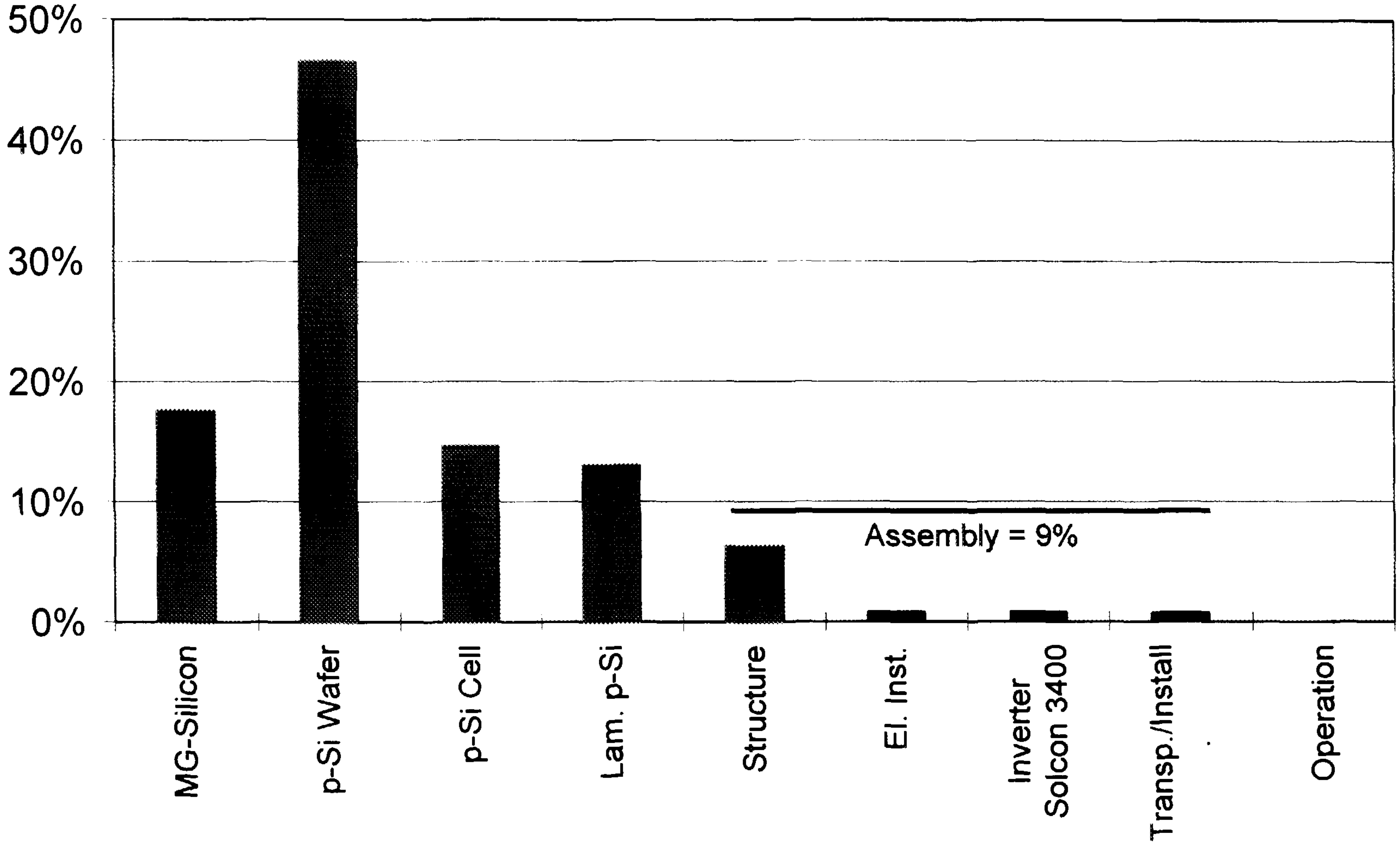
Relative Contributions from the Steps of PV chain to total GHG Emission associated with p-Si Slanted-Roof Integrated Panels



Source: Frischknecht et al., 1996

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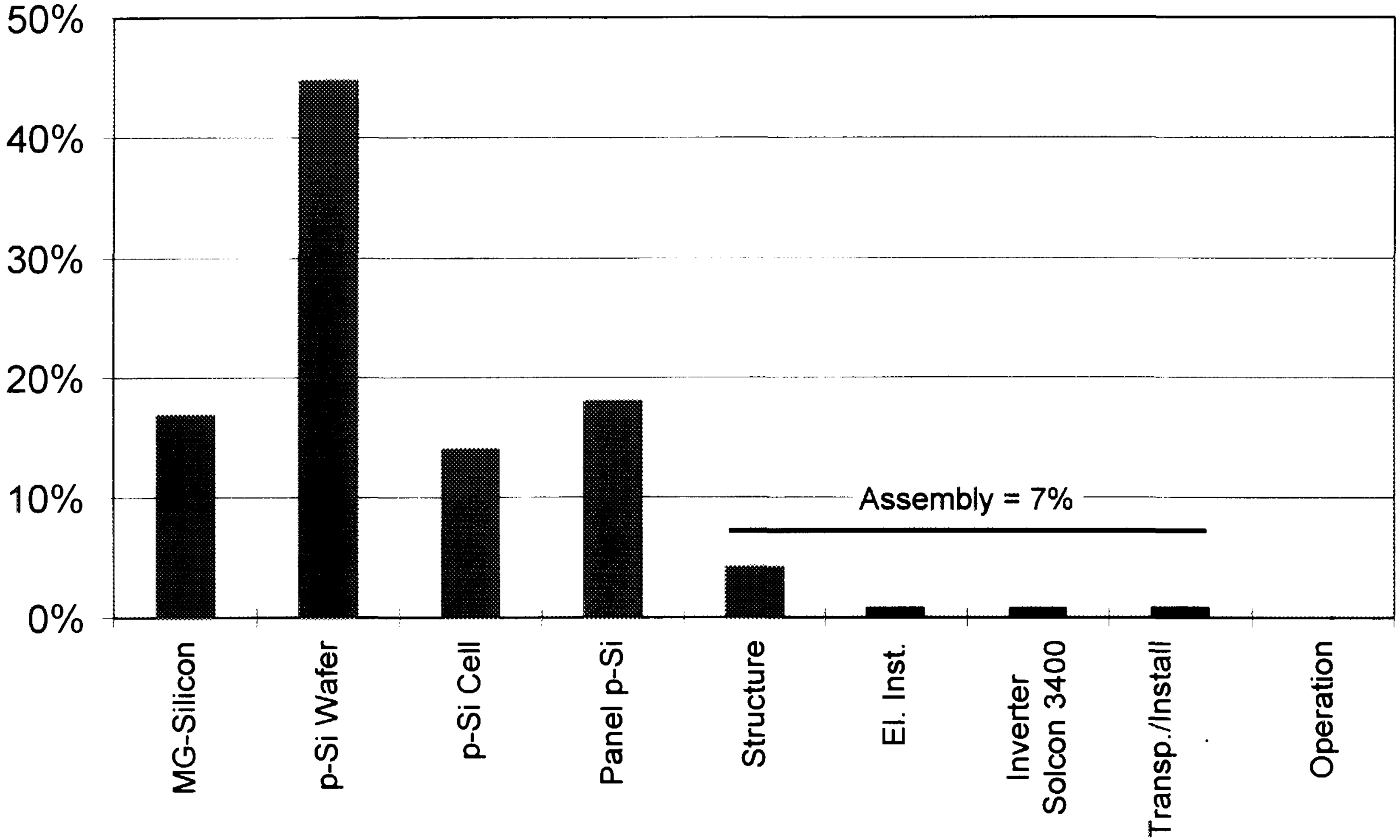
Relative Contributions from the Steps of PV chain to total GHG Emission associated with p-Si Slanted-Roof Panels



Source: Frischknecht et al., 1996

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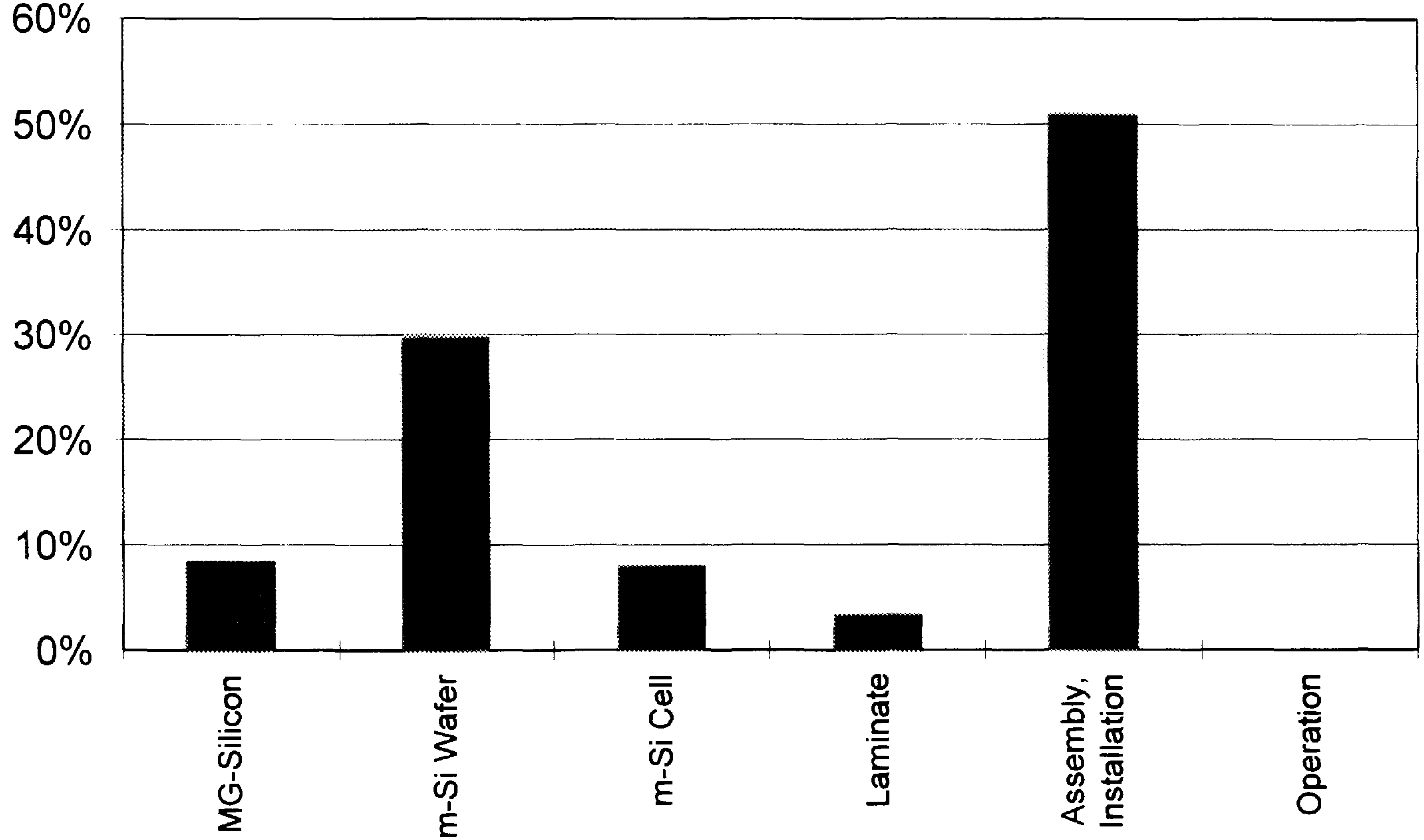
Relative Contributions from the Steps of PV chain to total GHG Emission associated with PHALK 500 Plant



Source: Frischknecht et al., 1994

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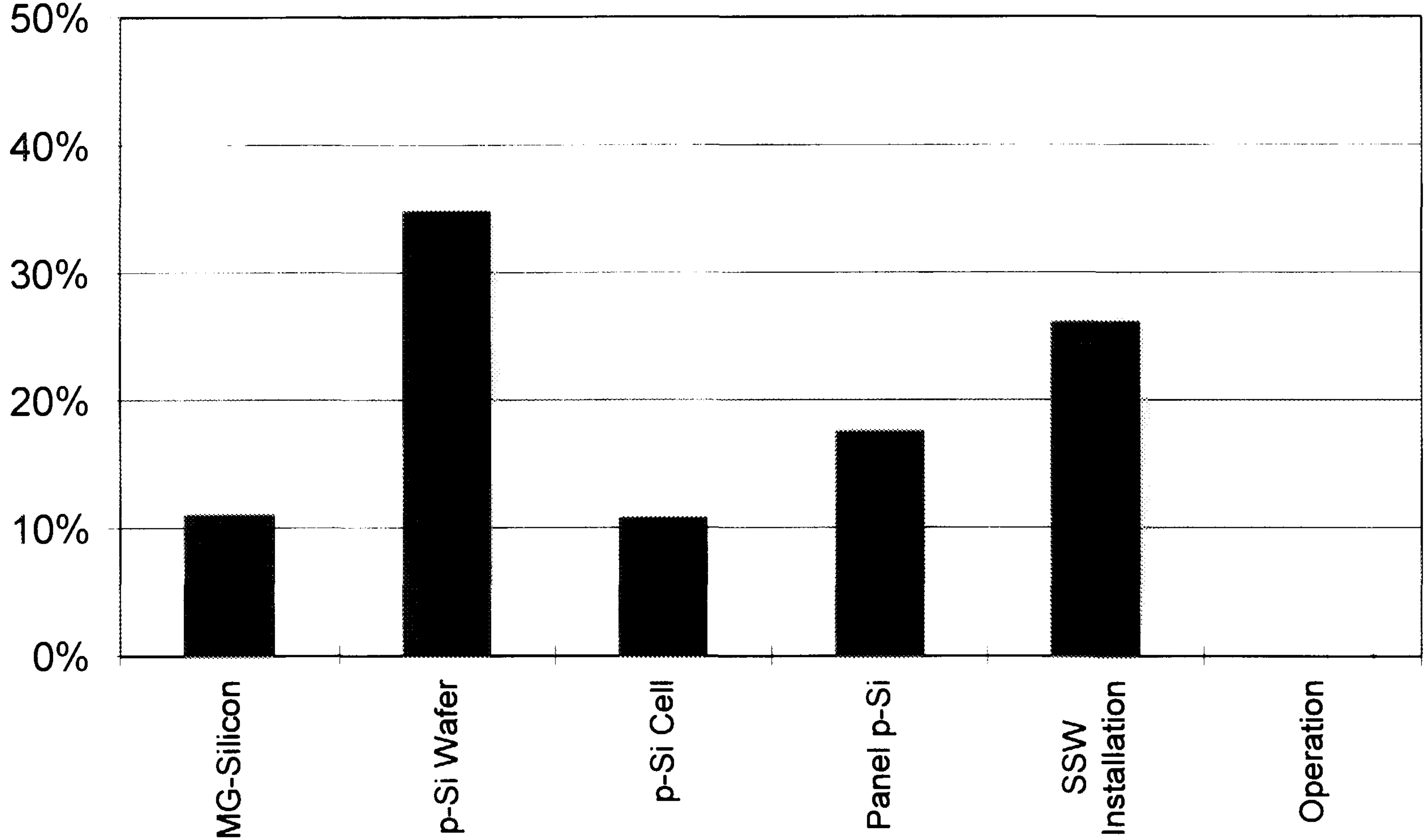
Relative Contributions from the Steps of PV chain to total GHG Emission associated with SSW 100 kW_p Plant



Source: Frischknecht et al., 1996

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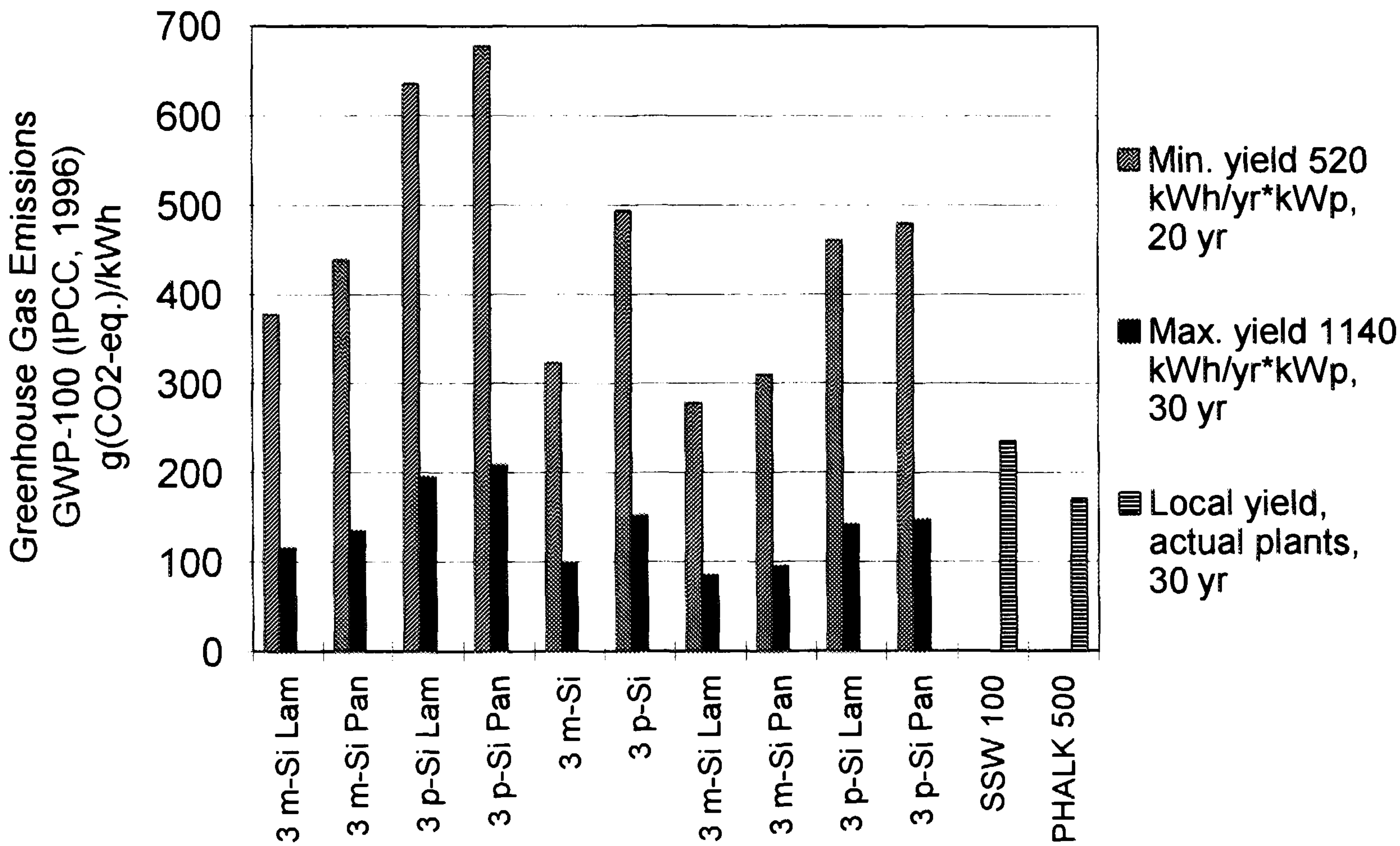
GHG Emissions associated with Photovoltaic in Switzerland: Range of values for the Middle Lands and Pre Alps



After Frischknecht et al., 1996, 1994

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Some characteristics of the assessed future photovoltaic technologies

Assessed technology	monocrystalline, ribbon-pulled wafers	triple-junction-cells from amorphous silicon
Represented technology	crystalline silicon technology	thin film technology
Thickness of the active layer	150 μm m-Si	≈ 0.5 μm a-Si
Panel efficiency	18%	10%
Total area per panel	0.43 m^2	1 m^2
Photoactive area per panel	0.35 m^2	1 m^2
Nominal power	64.8 W_p	100 W_p
PV plant share in years 2020/30 in CH (assumed)	80%	20%

Source: Dones et al., 1996

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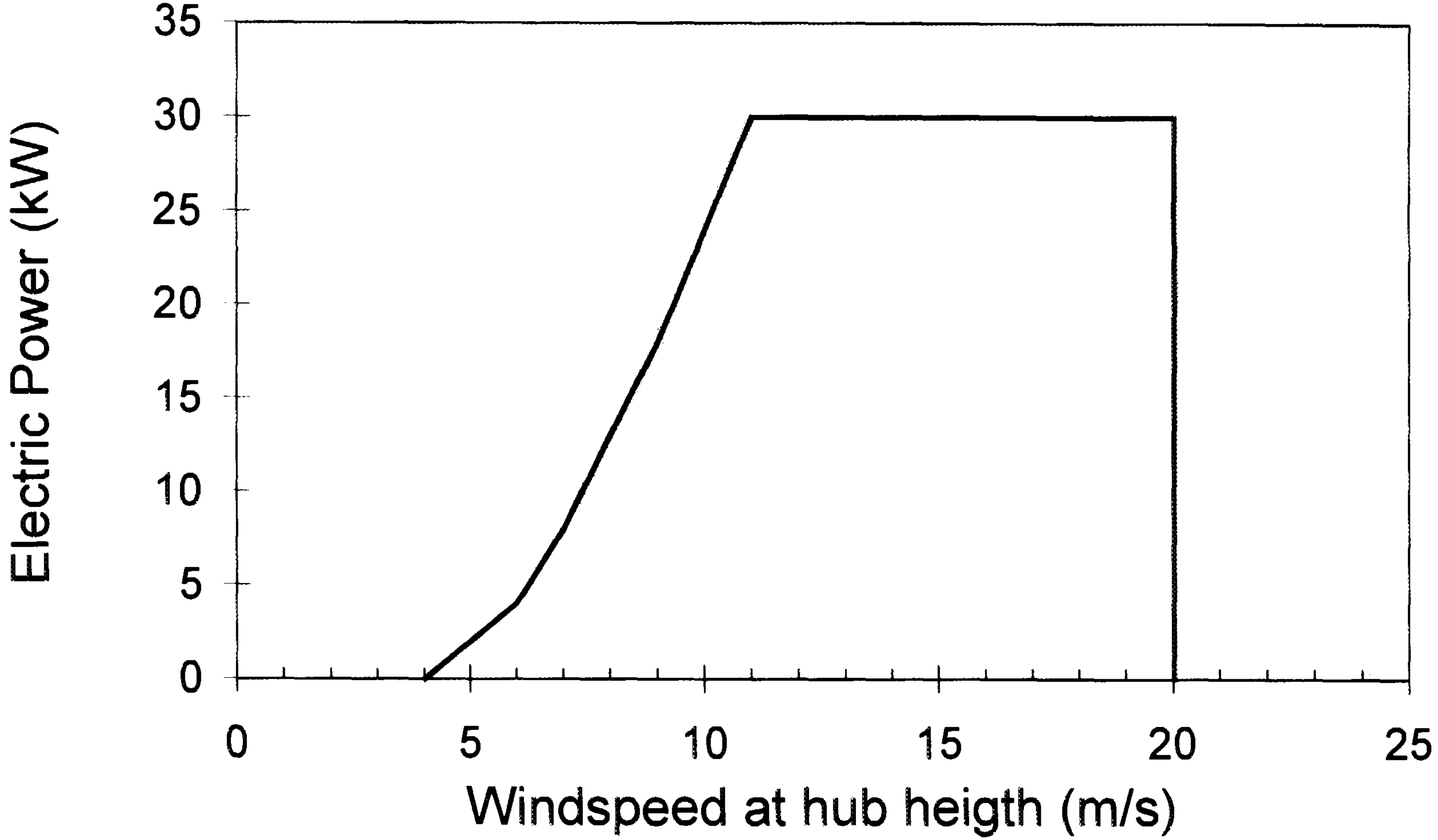
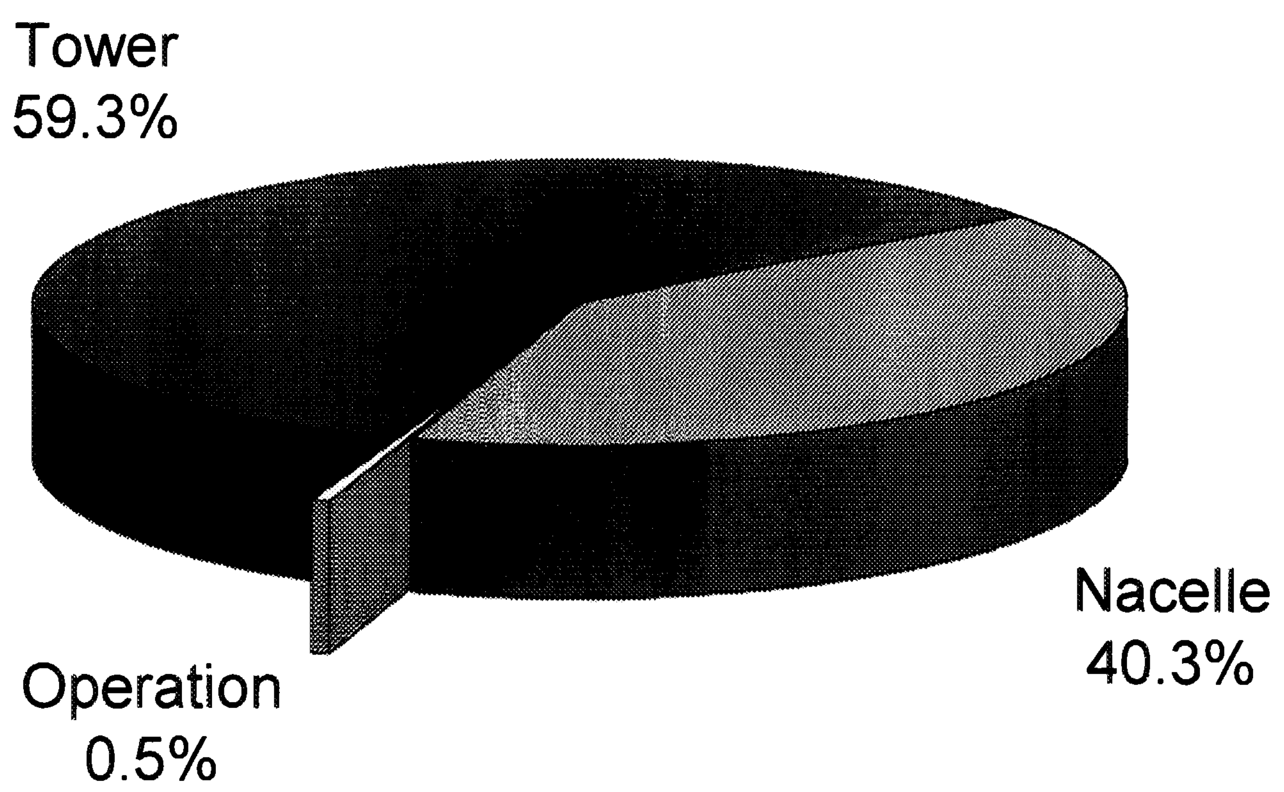
Simplon Wind Plant Power Curve



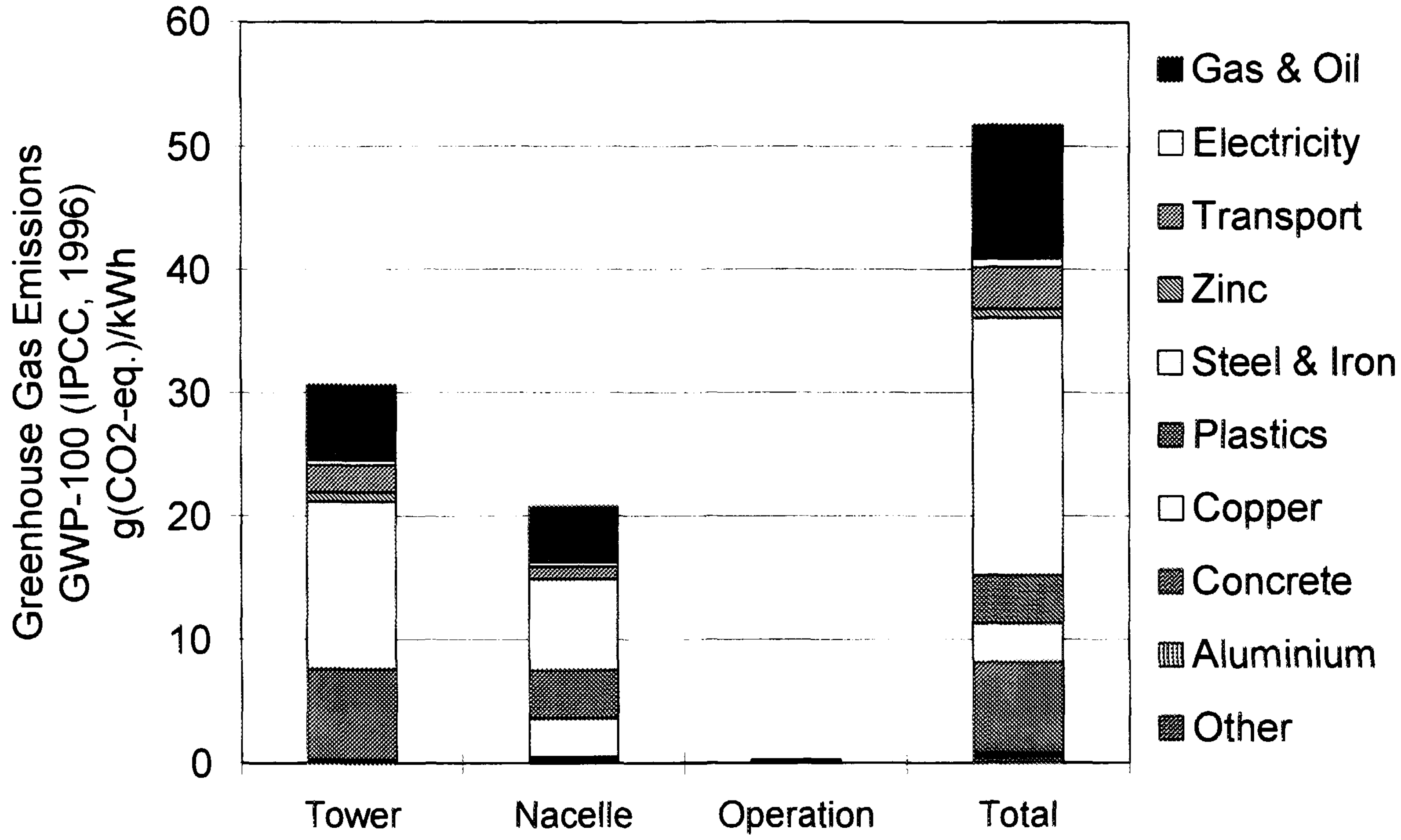
Source: Frischknecht et al. 1996

Shares of GHG Emissions associated with the Simplon 30 kW Wind Power Plant



Source: Frischknecht et al. 1996

Contributions (absolute values) to total GHG Emission associated with the Simplon 30 kW Wind Plant



Source: Frischknecht et al. 1996

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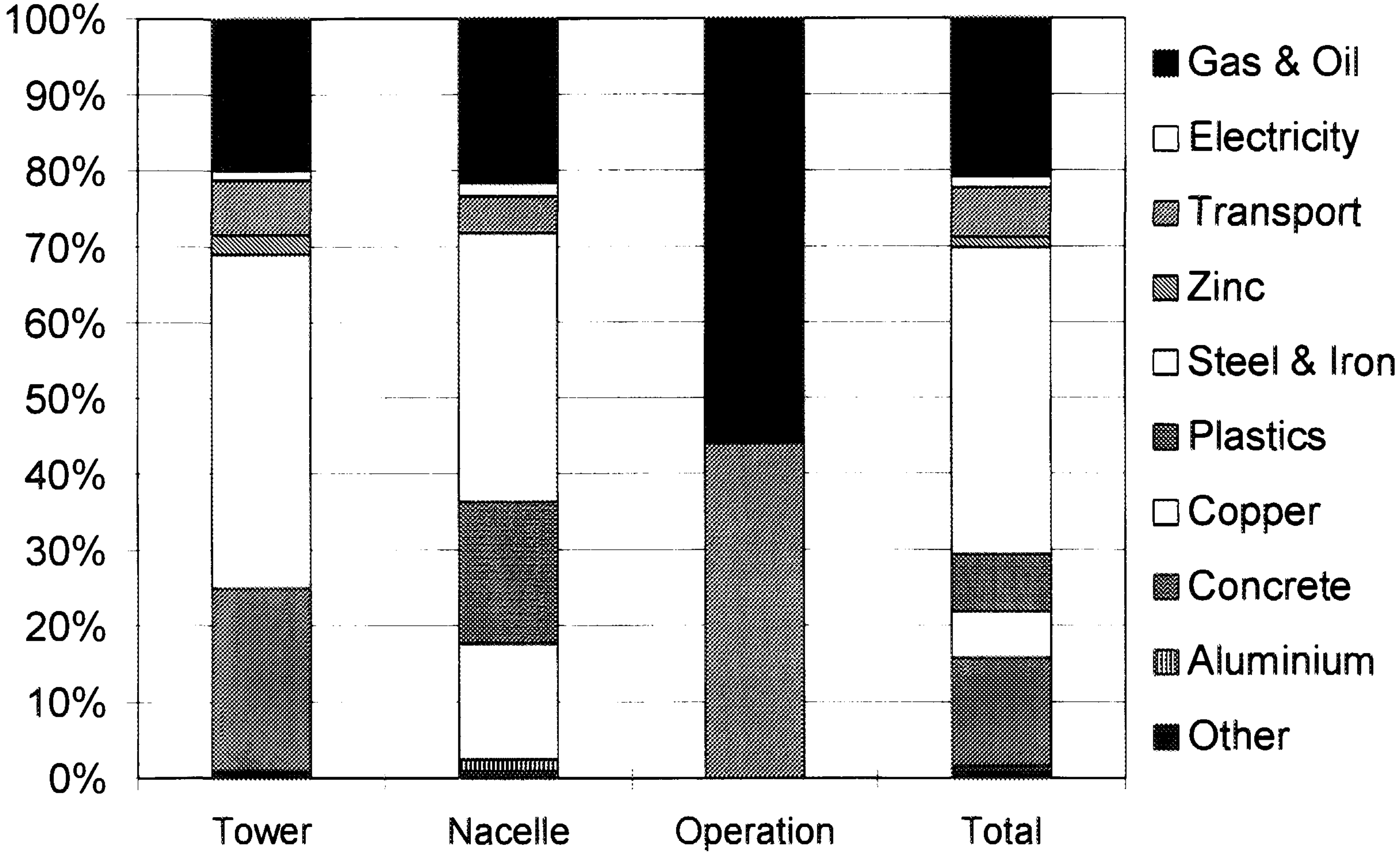
Contributions (relative values) to total GHG Emission associated with the Simplon 30 kW Wind Plant



Source: Frischknecht et al. 1996

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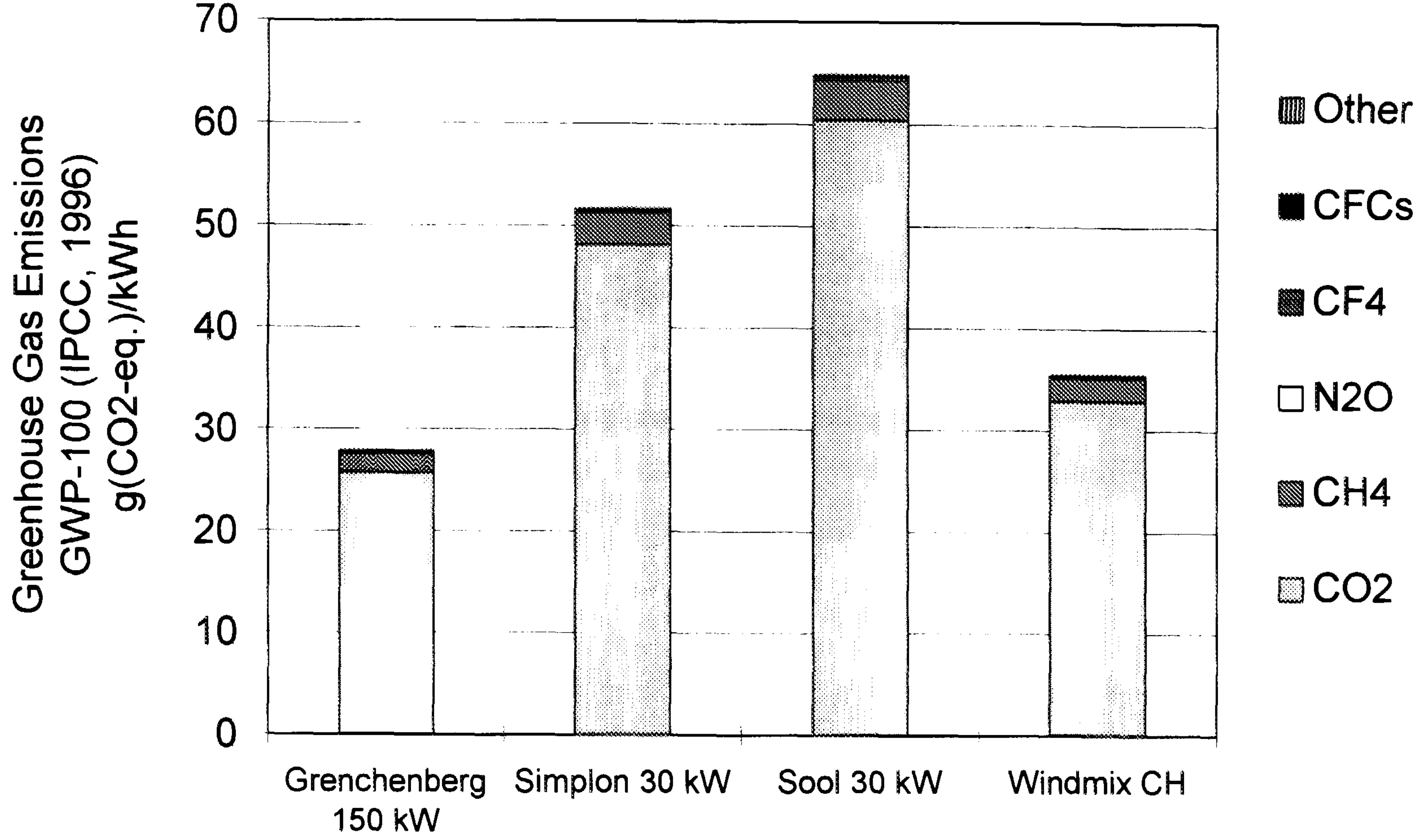
GHG Emissions associated with three Swiss Wind Plants



Source: Frischknecht et al. 1996

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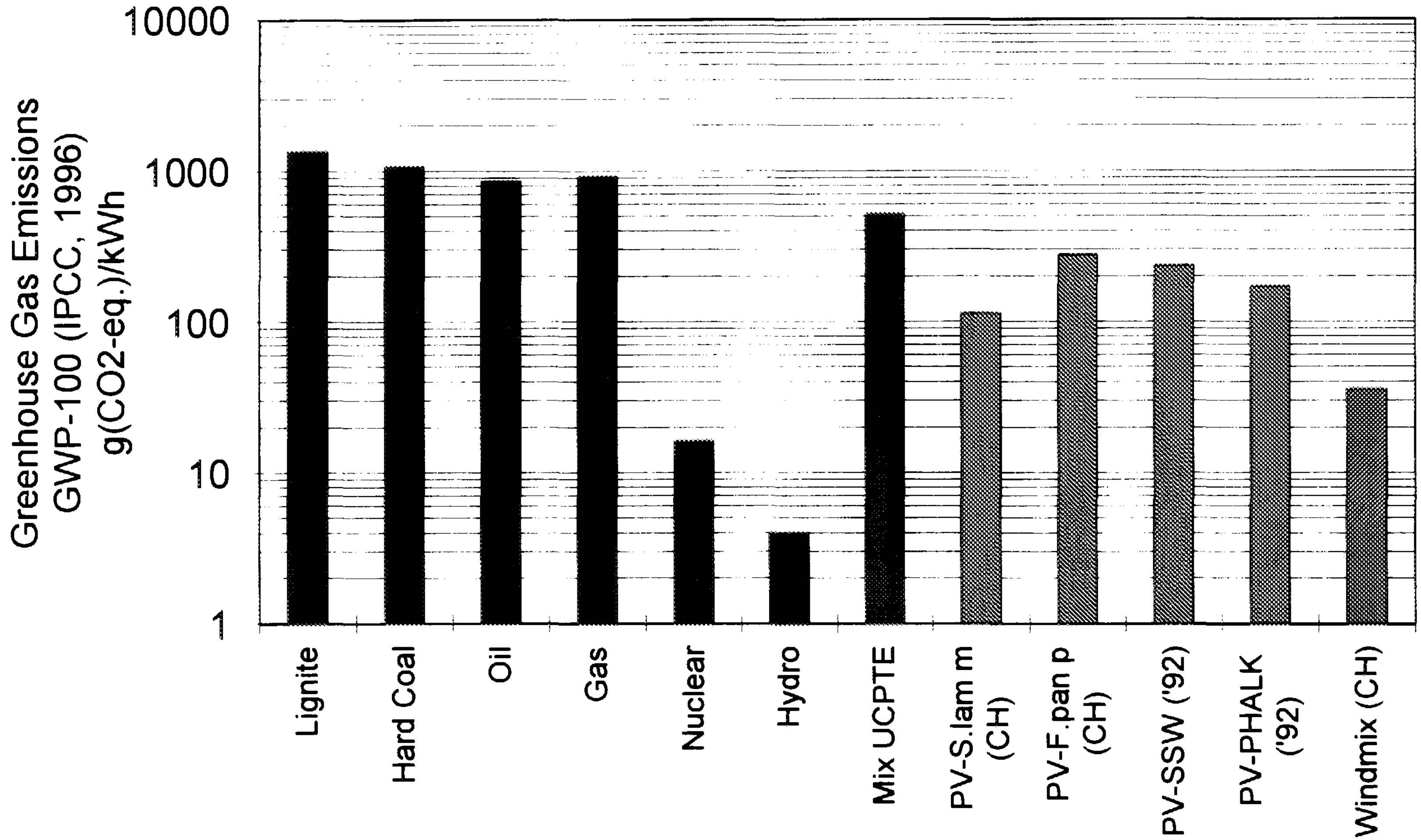
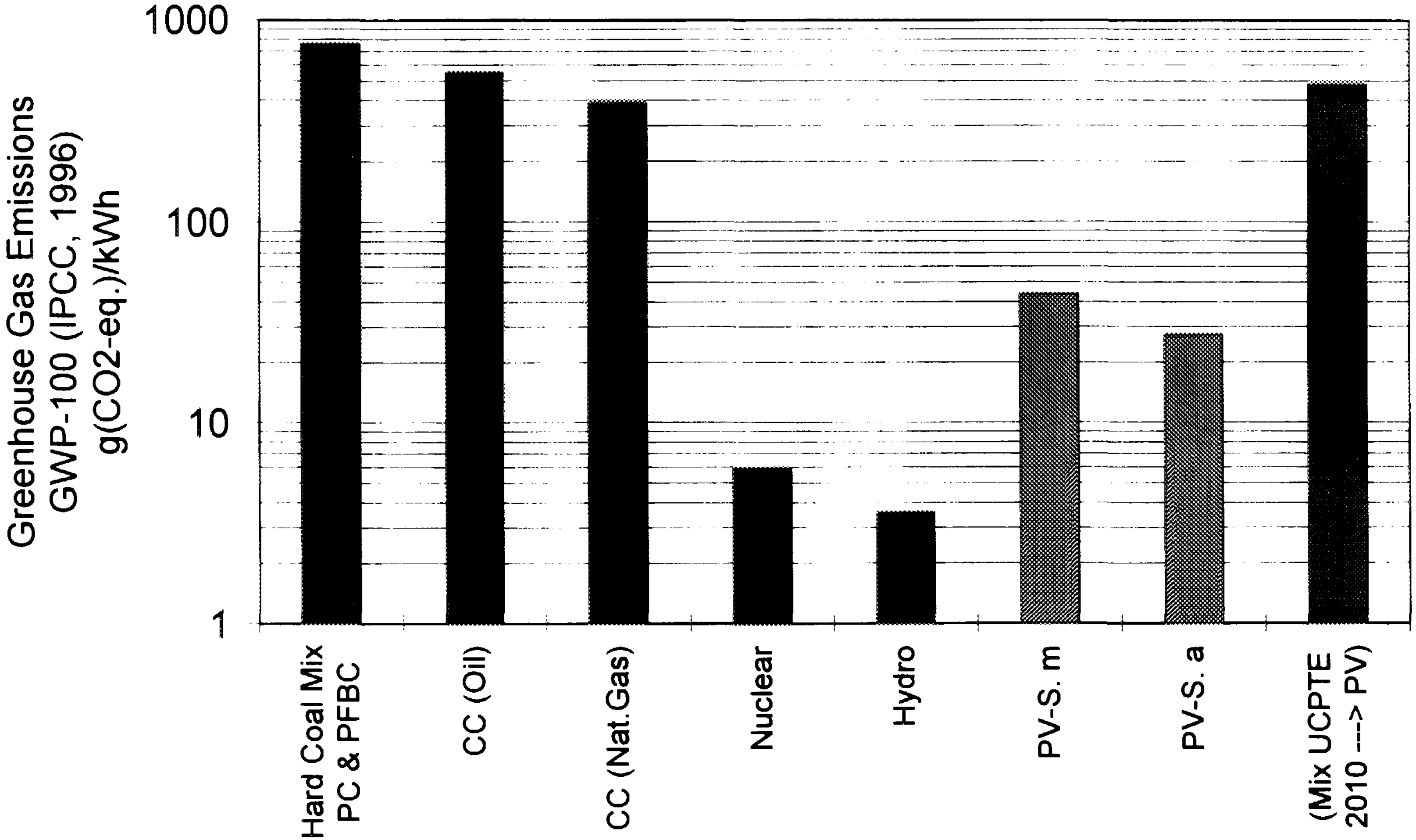
Comparison of GHG Emissions from Electricity Generating Systems: UCPTE Systems and Mix vs. PV & Wind Plants in Switzerland



Source: Frischknecht et al., 1994, 1996

Comparison of GHG Emissions associated with Future Electricity Systems in Switzerland (year 2030)



Source: Dones et al., 1996

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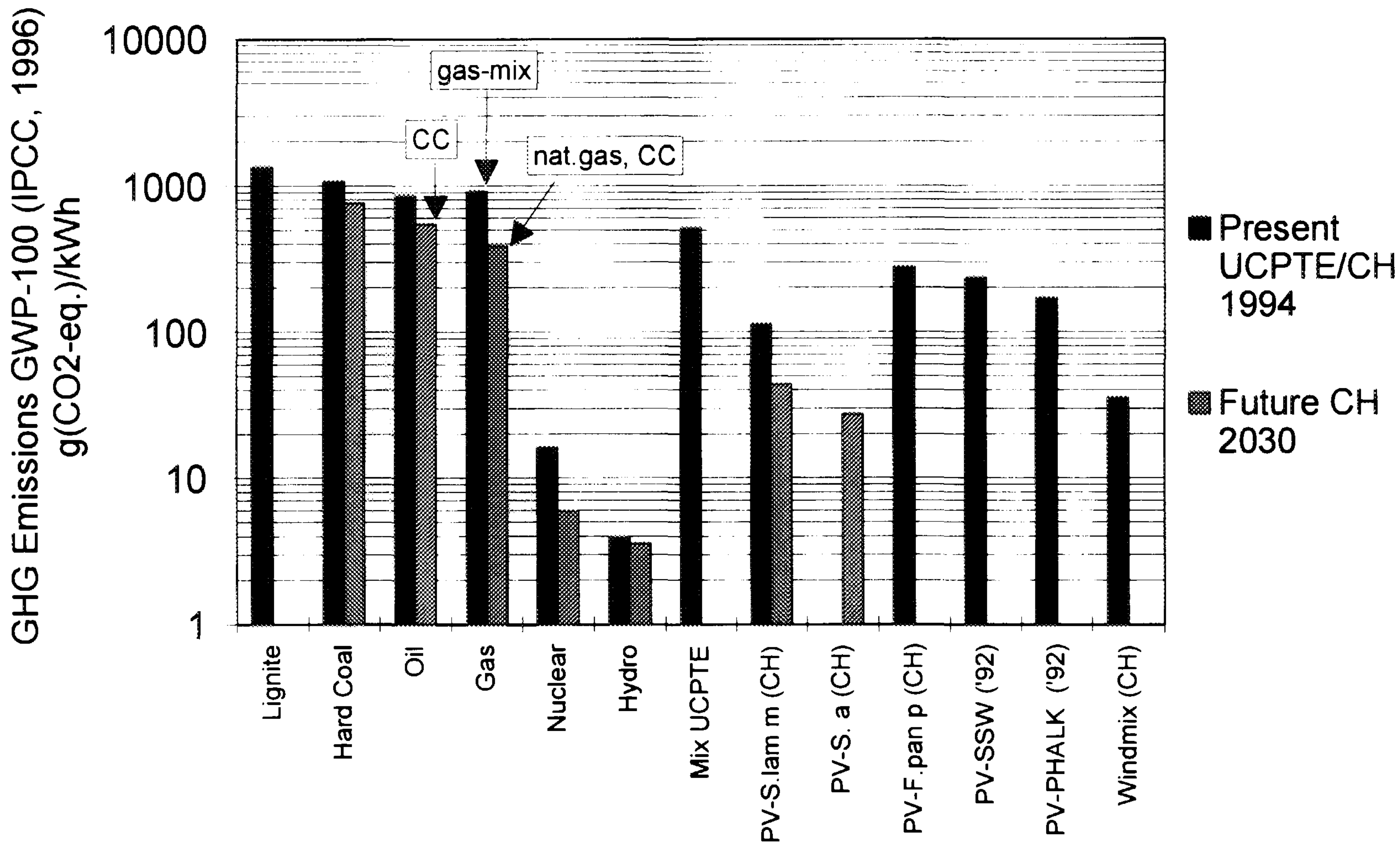
Comparison of GHG Emissions: Present UCPTE/Swiss vs. Future Swiss Electricity Systems



Sources: Dones et al., 1996; Frischknecht et al., 1994, 1996

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