CARBON- AND ENVIRONMENTAL FOOTPRINTING OF PHOTOVOLTAIC MODULES

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ABSTRACT: Upcoming building regulations in the framework of sustainable building policy will require reliable, producer-specific data on the environmental profile of PV products. Carbon footprinting is an important aspect of environmental sustainability reporting but a fair comparison can only be made when all environmental footprints of a product are taken into account. Also different LCA databases (for example ecoinvent, Gabi and ELCD) will generate different results. Many PV module producers have performed a carbon footprint analysis but because various methodologies and assumptions are used a good comparison is not possible. ISO 14067-1 is the internationally leading (draft) standard for carbon footprinting of products. No Product Footprint Category Rules (PFCR) or Product Category Rules (PCRs) for Photovoltaics exist and it is recommended to use IEA PVPS task 12 guidelines. New LCA data for commercial production of crystalline silicon-, amorphous silicon, CIGS and CdTe glass-based PV modules are compiled and show decreased power and material consumption.
Keywords: environmental effect, energy payback time, carbon footprint, building integration

1 PV AND SUSTAINABLE BUILDING POLICY

PV technology is expected to play an increasing role in the construction of sustainable buildings. At the same time we can observe that many European countries are looking at LCA-based instruments to measure the sustainability performance of such buildings.

For example in the Netherlands a calculation of the Environmental Performance of Buildings (MPG) is obligatory for new residential and office buildings from 1 January 2013. Without such a calculation no building permit will be issued. It is to be expected that other European countries (Germany, France) will follow with similar regulation in the near future.

Environmental product data for building products are necessary for such assessments. The Dutch building industry has therefore set up a National Database with Environmental Product Data. PV panels are included in this database on basis of data which are relatively old (2005) and not producer-specific. Only three types of PV modules are distinguished c-Si (mono+multi), a-Si foil and CdTe.

Because of the design of the assessment scheme PV systems will show a negative effect on the environmental impact score of the building. The reason for this is that only the impacts of materials in the building are assessed in the MPG-score but not the positive effect of PV energy production. Energy output is included in a separate building performance score: the energy performance score. The latter performance score is required and prescribed by the European Energy Performance Directive for Buildings (EPBD).

The negative effects of PV components on the material impact score may discourage architects to include a PV system in their building design. This effect will be enhanced by PV product data which are too pessimistic.

Moreover, PV producers who can show that their product has a better environmental performance than the generic profile can expect a boost for their market share in the building sector. As was shown by de Wild-Scholten [1], full consideration of the specific production locations can have a significant positive or negative effect on the environmental impact score of PV panels.

The bottom line is that reliable, producer-specific data on the environmental profile of PV products are become increasingly important to ensure a fair treatment of PV systems on buildings. Upcoming building regulations in the framework of sustainable building policy will strengthen this trend. PV producers should act proactively to prevent a negative image among building designers and a loss of market share in the building sector.

2 CARBON FOOTPRINTING

A leading carbon footprint is a market differentiator and creates an effective Unique Selling Point. This will help to build a premium brand which allows premium pricing and will increase sales. The attitudes of PV module customers towards carbon footprint certification are shown in Figure 1. Manufacturers of solar cells and modules have acknowledges this and ordered certified carbon footprint studies (Table I). Unfortunately all LCA results remain confidential.

Various specifications/guidelines/standards exist for carbon footprinting. PAS 2050 is a British specification (not a standard!) and was released in 2008. The The international Greenhouse Gas Protocol (GHG Protocol) was released September 2011. ISO 14067-1 "Carbon footprint of products" is the international standard. The final version of ISO 14067-1 is expected 2013-04-15 but the draft version is already available and used. Table II shows that different carbon footprint methods and implementations will lead to different results.

Table III shows carbon footprint results for crystalline silicon PV modules from various studies [2-5]. Due to different electricity mixes used it is not possible to make a good comparison of the technologies used.

In addition to this different LCA databases needed for other data will generate different results. The ecoinvent database is the most transparent, the ELCD database is very incomplete and the Gabi database is not transparent.

To overcome problems associated with the use of different methodologies, assumptions and databases Product Footprint Category Rules (PFCR) or Product

Category Rules (PCRs) for Photovoltaics are needed. However PFCR/PCRs do not exist for Photovoltaics and it is recommended to use the IEA PVPS task 12 guidelines instead [6].

A reliable certified environmental footprint of PV modules can be performed by an LCA commissioner who is 1) competent, which means having experience in Life Cycle Assessment of Photovoltaics, 2) uses best & up-to-date software & databases, 3) has a systematic approach, 4) provide transparent documentation so others can reproduce the LCA results and 5) is independent.

3 LCA DATA PV MODULES

Older data sets for PV modules are available in for example [7].

New LCA data for commercial production of crystalline silicon-, amorphous silicon, CIGS and CdTe glass-based PV modules are compiled and show decreased power and material consumption [8]. The following datasets have been updated to status 2011:

- monocrystalline silicon crystal,
- multicrystalline silicon ingot,
- monocrystalline silicon wafer,
- multicrystalline silicon wafer,
- monocrystalline silicon solar cell,
- multicrystalline silicon solar cell,
- crystalline silicon PV module,
- a-Si PV module,
- CIGS PV module,
- CdTe PV module.

The major data are based on 2011 manufacturers' data and 2011 values the International Technology Roadmap for Photovoltaics (ITRPV 2012). These data are verified by comparison with data from equipment- and materials manufacturers (status 2011/2012). Two examples are presented here: 1) EVA encapsulation foil amount per 1.6 m^2 module (Table IV) and 2) Power consumption for Czochralski crystal growth (Table V, Figure 2).

EVA foil amount in the ecoinvent 2.2 database is 1.6 kg per 1.6 m^2 module. The 2011 data from ITRPV [9] give 450 micron thickness, combined with 0.955 g/cm^3 density (average [11]), 2 layers EVA, cutting loss 1% [9] results in 1.376 kg/m^2 which value is also adopted by SmartGreenScans [8]. Average data from the EVA market survey study by Schmela [11] give 466 micron thickness and with the same assumptions as above result in 1.424 kg/module which is very close to the value of 1.376 kg/m^2. It must be pointed out that the market survey provides an overview of EVA foils on the market but has no data on market share of the various foils.

Power consumption for the growth of Czochralski monocrystalline silicon crystals for solar applications in the ecoinvent 2.2 database is 85.6 kWh/kg crystal. Manufacturers data collected by SmartGreenscans has a value of 68.2 kWh/kg crystal. Data from equipment manufacturers are taken from Chunduri (2012). The average power consumption is multiplied with the cycle time to get the average power consumption per cycle. From the maximum charge in the crucible 20 kg (guess) was subtracted to obtain the mass of silicon crystal grown per cycle. It is assumed that the same amount of electricity is needed to cool the cooling water (worst case assumption). The average value obtained for all Cz crystal growing equipment is 58 kWh/kg crystal. When taking the typical value for the growth of a 165 kg crystal [9] we obtain a value of 50 kWh/kg crystal. The market survey of equipment does not have information about market shares. The value of 85.6 and 68.2 kWh/kg crystal also include power consumption for other than crystal growing like clean room air conditioning and poly-silicon cleaning. The value of 68.2 is an acceptable value.

4 CONCLUSIONS

Increasing the accuracy, transparency, comparability and reliability of carbon- and environmental footprint analysis of PV modules can be achieved by 1) the use of international ISO standards, 2) the use of IEA PVPS task 12 LCA guidelines for PV, 3) the use of recent LCA data sets of PV modules and its components.

5 ACKNOWLEDGEMENTS

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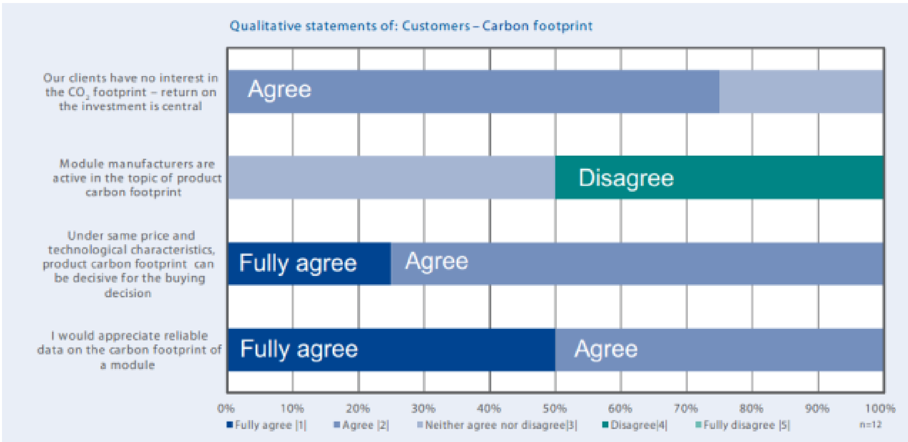

Figure 1: Market research into the attitudes of PV module customers towards carbon footprint certification by EuPD Research

Table I: Certified carbon footprint studies announced by solar cell and PV module producers

	The study			Product data				Carbon Footprint results				
Manufacturer	Standard	LCA-Commissioner	Report	Data	Product name	Type	Area	Raw materials	Manufacture	Distribution/Retail	Consumer use	Disposal/recycling
SOLAR CELLS x-Si												
Motech Solar	PAS2050:2008	SGS	2010	2009	IM156	multicrystalline Si		89.4%	10.2%	0.4%		
				2008	IM156	multicrystalline Si						
MODULES x-Si												
AOU	PAS2050:2008	SGS	2010		PM220P00	multicrystalline Si	1.7 m2	82.0%	17.0%	1.0%		
CNPV Solar Power	ISO14067	TüV Rheinland	2012			monocrystalline Si						
						multicrystalline Si						
Jinko Solar		TüV Rheinland	2012									
Upsolar		Bureau Veritas	2012		UP-M185M	monocrystalline Si	1.3 m2					
					UP-M230P	multicrystalline Si	1.6 m2					
Yingli Solar	PAS2050:2011	TüV Rheinland	2011			monocrystalline Si						
						multicrystalline Si						
MODULES TF-Si												
NexPower	PAS2050:2008	DNV (Det Norske Veritas)	2011									

Table II: Characteristics of carbon footprint methods

ISO14067		In Simapro 7.3.3 / ecoinvent 2.2:	IPCC2007 GWP100a v1.02	Greenhouse Gas Protocol v1.01
dLUC = direct Land Use Change; **iLUC** = indirect Land Use Change				
GHG emissions and removals arising from fossil carbon sources and sinks	+	Fossil based carbon (carbon originating from fossil fuels): carbon dioxide; carbon dioxide, fossil; methane; methane, fossil	+, excluding carbon monoxide!	+, including carbon monoxide!
GHG emissions and removals arising from biogenic carbon sources and sinks	+	Biogenic carbon (carbon originating from biogenic sources such as plants and trees): carbon dioxide, biogenic; methane biogenic	-	+, including carbon monoxide biogenic!
GHG emissions and removals resulting from dLUC	+	Carbon from Land transformation (direct impacts): carbon dioxide, land transformation	+	+
Soil carbon change, if not already calculated as part of LUC	If calculated			
GHG emissions and removals resulting from iLUC	If calculated	Carbon from Land transformation (indirect impacts)	-	-
Non-CO2 GHG emissions and removals arising from livestock, manure or soils	+			
GHG emissions resulting from aircraft transportation	+			
Effect of carbon storage arising from the use stage and/or end-of-life stage of products	If calculated			
		Carbon uptake (CO2 that is stored in plants and trees as they grow): carbon dioxide, in air	-	+

Table IIIa: Details of LCA studies presented by crystalline silicon PV module manufacturers

	Reference	Manufacturers, Date	multi or mono	Details	Module efficiency	Irradiation on optimized-angle	Performance ratio	Life expectancy
						$kWh/m^2.yr$		years
1	Westgaard 2012	REC 2011-Q1	multi	US poly-Si blend with FBR, wafers/cells Norway, modules Singapore, Peak Energy series multicrystalline Si modules, module efficiency ...	?	1700	0.84	30
2	Westgaard 2012	REC 2011-Q1	multi	US poly-Si blend with FBR, wafers/cells/modules Singapore, Peak Energy series multicrystalline Si modules, multi module efficiency ...	?	1700	0.84	30
3	Wetzel 2011	Wacker, Bosch, Solar World 2010	mono	poly-Si Wacker DE (CHP, hydro, German electricity), wafers/cells/modules Germany	15.0%	1700	0.75	30
4	Wetzel 2011	Wacker, Bosch, Solar World 2010	multi	poly-Si Wacker DE (CHP, hydro, German electricity), wafers/cells/modules Germany	13.9%	1700	0.75	30
5	Müller-Pelzer 2012	Wacker, Bosch, Solar World 2011	multi	poly-Si Wacker DE (CHP, hydro, German electricity), wafers/cells/modules Germany	?	1700	0.75	30
6	de Wild 2012	Elkem Solar Silicon 6000 MT	multi	ESS Norwegian electricity, wafers/cells/module PV world electricity	14.3%	1700	0.75	30
7	de Wild 2012	Siemens-type poly-Si (ecoinvent 2.2)	multi	poly-Si hydro&CHP, wafers/cells/module PV world electricity	14.3%	1700	0.75	30

Table IIIb: Energy payback time and carbon footprint results presented by crystalline silicon PV module manufacturers

	Reference	Manufacturers, Date	multi or mono	CED of solar grade Si	CED of module	EPBT of module	EPBT of PV system	CF of solar grade Si	CF of module	CF of module	CF of PV system
				MJ/kg Si	MJ/Wp	years	years	kg CO_2-eq/kg Si	g CO_2-eq/Wp	g CO_2-eq/kWh	g CO_2-eq/kWh
1	Westgaard 2012	REC 2011-Q1	multi	?	13.0	0.8	1.1	?	570	12	18
2	Westgaard 2012	REC 2011-Q1	multi	?	15.2	0.9	1.2	?	726	15	21
3	Wetzel 2011	Wacker, Bosch, Solar World 2010	mono	?	?	1.3	1.5	?	?	?	?
4	Wetzel 2011	Wacker, Bosch, Solar World 2010	multi	?	?	1.1	1.3	?	?	?	?
5	Müller-Pelzer 2012	Wacker, Bosch, Solar World 2011	multi	?	?	0.86	?	?	800	?	?
6	de Wild 2012	Elkem Solar Silicon 6000 MT	multi	306	11.7	0.8	1.1	10.6	660	22	29
7	de Wild 2012	Siemens-type poly-Si (ecoinvent 2.2)	multi	961	14.5	1.0	1.3	39.8	874	25	33

Table IV: EVA encapsulation foils (Company data: Schmela 2012)

Company	Model	Standard thickness	Average thickness	Density	Mass / m2	Mass / m2	Cutting loss	Module area	Total EVA per 1.6 m2 module
					1 layer EVA	2 layers EVA			
		micron	micron	g/cm3	kg / m2	kg/m2	%	m2	kg / module
Stevens Urethane	EncapsolarCool PV-7190: thermal conductive	460	460	1.27	0.584	1.168	1%	1.6	1.870
Bridgestone	EVASKY	460 - 500 - 600	520	0.95	0.494	0.988	1%	1.6	1.581
Decent Plastic	Decent-JM50-EA	450 - 500	475	0.95	0.451	0.903	1%	1.6	1.444
Evasa	FC100011E/A	460	460	0.96	0.442	0.883	1%	1.6	1.413
Evasa	UC100031E/A	460	460	0.96	0.442	0.883	1%	1.6	1.413
Evasa	SC100041E/A	460	460	0.96	0.442	0.883	1%	1.6	1.413
First PV Material	EVA Film F806	450 - 500	475	0.95	0.451	0.903	1%	1.6	1.444
First PV Material	EVA Film F406	450	450	0.95	0.428	0.855	1%	1.6	1.368
First PV Material	EVA Film Su-806	450	450	0.95	0.428	0.855	1%	1.6	1.368
First PV Material	EVA Film F806-W	450	450	0.95	0.428	0.855	1%	1.6	1.368
Mitsui Chemicals	SOLAR EVA SC52B	450 - 600	525	0.95	0.499	0.998	1%	1.6	1.596
Mitsui Chemicals	SOLAR EVA RC02B	450	450	0.95	0.428	0.855	1%	1.6	1.368
Mitsui Chemicals	SOLAR EVA RCT1B	450	450	0.95	0.428	0.855	1%	1.6	1.368
NovoGenio	EVA NovoSolar NC	420	420	0.96	0.403	0.806	1%	1.6	1.290
NovoGenio	EVA NovoSolar FC	420	420	0.96	0.403	0.806	1%	1.6	1.290
NovoGenio	EVA NovoSolar FCLV	420	420	0.96	0.403	0.806	1%	1.6	1.290
NovoPolymers	NovoVellum FC3	380 - 450 - 500	443	0.96	0.426	0.851	1%	1.6	1.362
NovoPolymers	NovoVellum UFC4	380 - 450 - 500	443	0.96	0.426	0.851	1%	1.6	1.362
NovoPolymers	NovoVellum MF01	400 - 450 - 500	450	0.96	0.432	0.864	1%	1.6	1.383
NovoPolymers	NovoVellum FW01: white/light reflection	450 - 500	475	0.96	0.456	0.912	1%	1.6	1.459
Saint-Gobain	LightSwitch Encapsulant EVA	200 - 450 - 500 - 660	453	0.96	0.434	0.869	1%	1.6	1.390
Sanvic	K-series	400 - 600	500	0.95	0.475	0.950	1%	1.6	1.520
Sanvic	F-series	450	450	0.95	0.428	0.855	1%	1.6	1.368
Sanvic	U-series	450	450	0.95	0.428	0.855	1%	1.6	1.368
SKC	ES2N	400 - 500 - 600	500	0.95	0.475	0.950	1%	1.6	1.520
SKC	EF2N	450 - 500	475	0.95	0.451	0.903	1%	1.6	1.444
SKC	EF3N	450 - 500	475	0.96	0.456	0.912	1%	1.6	1.459
SKC	EU2N	450 - 500	475	0.95	0.451	0.903	1%	1.6	1.444
SKC	EF2T	450 - 500	475	0.95	0.451	0.903	1%	1.6	1.444
SKC	EF2W	450 - 500	475	0.95	0.451	0.903	1%	1.6	1.444
Solutia	VISTASOLAR 488.10	460	460	0.97	0.446	0.892	1%	1.6	1.428
Solutia	VISTASOLAR 486.xx/496.xx	460 - 500	480	0.96	0.461	0.922	1%	1.6	1.475
Solutia	VISTASOLAR 520.43	460 - 500	480	0.96	0.461	0.922	1%	1.6	1.475
Solutia	VISTASOLAR 520.68 UV Block	460 - 500	480	0.96	0.461	0.922	1%	1.6	1.475
Solutia	VISTASOLAR 520.78 UV Gain	460 - 500	480	0.96	0.461	0.922	1%	1.6	1.475
Stevens Urethane	PV-135	460	460	0.95	0.437	0.874	1%	1.6	1.399
Stevens Urethane	PV-130	460	460	0.95	0.437	0.874	1%	1.6	1.399
STR Solar	Photocap 15420P	460	460	0.96	0.442	0.883	1%	1.6	1.413
STR Solar	Photocap 15505P	460	460	0.96	0.442	0.883	1%	1.6	1.413
STR Solar	Photocap 15455P	460	460	0.96	0.442	0.883	1%	1.6	1.413
STR Solar	Photocap 15295P	460	460	0.96	0.442	0.883	1%	1.6	1.413
STR Solar	Photocap FC295P	460	460	0.96	0.442	0.883	1%	1.6	1.413
STR Solar	Photocap FC280P	460	460	0.95	0.437	0.874	1%	1.6	1.399
STR Solar	Photocap SC918P	460	460	0.96	0.442	0.883	1%	1.6	1.413
Toppan	EF1001	450	450	0.95	0.428	0.855	1%	1.6	1.368
Toppan	EF5001	450	450	0.95	0.428	0.855	1%	1.6	1.368
Yang Yi S&T	SC-3825, FC-3825, FC-0610B	500 - 600	550	0.96	0.528	1.056	1%	1.6	1.690
Yonggu Insulation	2008B	500	500	0.95	0.475	0.950	1%	1.6	1.520
Average EVA encapsulation foils:			**466**	**0.955**	**0.445**	**0.890**	**1%**	**1.6**	**1.424**
ecoinvent 2.2									**1.600**
ITRPV 2011 data			**450**	**0.955**	**0.430**	**0.860**	**1%**	**1.6**	**1.376**
SmartGreenScans LCA PV data set = ITRPV 2011 data									**1.376**

Table V: Power consumption for Czochralski silicon crystal growth (Company data: Chunduri 2012)

Company	Model	average power consumption	cycle time	max. charge	ingot	average power consumption / cycle	average power consumption / kg ingot	average power consumption / kg ingot
					20 kg pot scrap assumed			plus cooling (worst case)
		kWh/h	h	kg	kg	kWh	kWh/kg	kWh/kg
JYT	JRDL-800	55	30	60	40	1650	41.3	82.5
Yongtai Electric	YCZ6000	55	40	60	40	2200	55.0	110.0
Mitsubishi Materials	S2	55	35	65	45	1925	42.8	85.6
Jinglong	CZ-80A	48	40	70	50	1920	38.4	76.8
Kayex	CG6000	76	51	80	60	3876	64.6	129.2
GigaMat	XGX-10000	67	35	85	65	2345	36.1	72.2
Huasheng Tianlong	DRF85	45	36	90	70	1620	23.1	46.3
Ferrotec	FT-CZ2008A	48	42	95	75	2016	26.9	53.8
Jinglong	CZ-90AI	53	42	100	80	2226	27.8	55.7
Yongtai Electric	CF0905	55	45	120	100	2475	24.8	49.5
Chenhua	ZTT90	50	52	120	100	2600	26.0	52.0
Jinglong	JLCZ120	60	46	120	100	2760	27.6	55.2
Kayex	KX110	60	46	120	100	2760	27.6	55.2
JYT	JRDL-900	70	40	120	100	2800	28.0	56.0
Ferrotec	FT-CZ2208AE	59	49	120	100	2891	28.9	57.8
JSC PCMP	PCMP 1500/250	60	52	120	100	3120	31.2	62.4
PVA TePla	EKZ 2700	60	40	130	110	2400	21.8	43.6
Jiangnan Electric	TDR95-JN	60	57	135	115	3420	29.7	59.5
Rijing New Energy	NXRJ-CZ9524 OP	50	40	150	130	2000	15.4	30.8
Huasheng Tianlong	DRF95	45	45	150	130	2025	15.6	31.2
Kayex	KX170-22	55	56	150	130	3080	23.7	47.4
Yongtai Electric	CF1050	55	60	150	130	3300	25.4	50.8
Ferrotec	FT-CZ2408BZ	71	54	150	130	3834	29.5	59.0
Mitsubishi Materials	S3	75	52	150	130	3900	30.0	60.0
Mitsubishi Materials	S4	85	56	170	150	4760	31.7	63.5
Jiangnan Electric	TDR105-JN	65	58	180	160	3770	23.6	47.1
PVA TePla	SolarCrystallizer 22/24	60	52	200	180	3120	17.3	34.7
PVA TePla	EKZ 3500	70	48	200	180	3360	18.7	37.3
Kayex	KX170	70	65	200	180	4550	25.3	50.6
Rijing New Energy	NXRJ-CZ105028 OP	60	50	260	240	3000	12.5	25.0
Average Czochralski crystal growth:		**60**	**47**	**131**	**111**	**2857**	**29.0**	**58.0**
Czochralski crystal growth of 165 kg ingot:							**25.0**	**50.0**
ecoinvent 2.2 database "CZ single crystalline silicon, photovoltaics, at plant/RER U"								**85.6**
LCA PV dataset SmartGreenScans								**68.2**

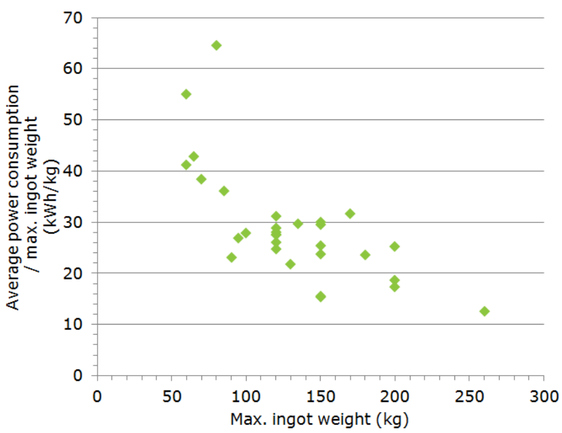

Figure 2: Average power consumption per max. ingot weight versus max. ingot weight for Czochralski silicon crystal growth (Data from Chunduri 2012)