CARL VON OSSIETZKY universität OLDENBURG

MERRA-based study of the wind/solar resource and their complementarity to the hydro resource for power generation in Colombia

Master Thesis

M.Sc. Renewable Energy (PPRE)

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Inter-American Development Bank

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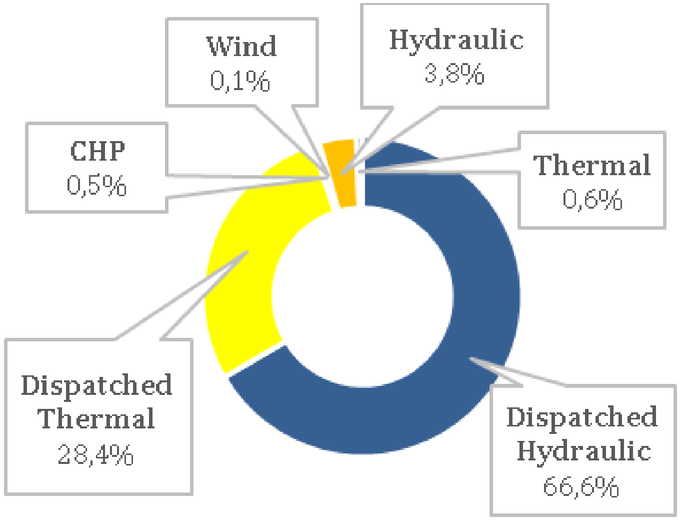
Contents

- Motivation and Research question
- Methodology
- Results and analysis
- Main conclusions

- Colombia´s installed capacity: 15.522MW
  - **Large hydro** (>20MW): **~ 67%**
  - Thermal : ~ 29% (**mostly** running on natural **gas**)

+Weather variability → Large droughts

- 1992: Strong national **shortages**
- 1998: very **high** spot **prices**
- 2003: Electricity **rationing** programs



*Own graph

+Difficulties increasing in execution of **conventional** large power plants (**environmental** and **social**)

- 2010: A 400MW hydro power plant stopped indefinitely

+A national **deficit** of natural **gas foreseen** in 2022 (medium scenario)

Energy community: ...maybe other sources?

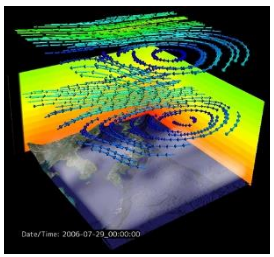
For power production in Colombia…

how complementary are the **intra-annual** distributions of the **wind** and **solar** resources of the country to the **hydro resources** found in sites where the **current hydro power plants** are located?

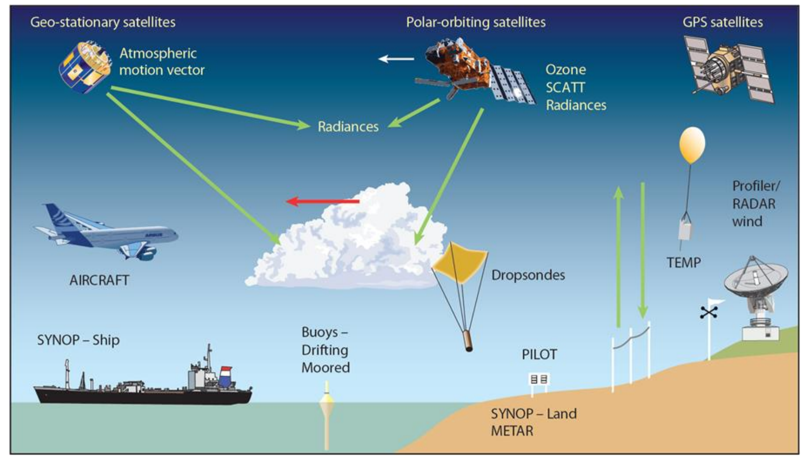
http://1.bp.blogspot.com/-AdexjjI44wE/TsJxVFnCohI/AAAAAAAAA6U/4Ij2-16k8h8/s1600/Figure+1+World+Map+Colombia.png

Reanalysis data

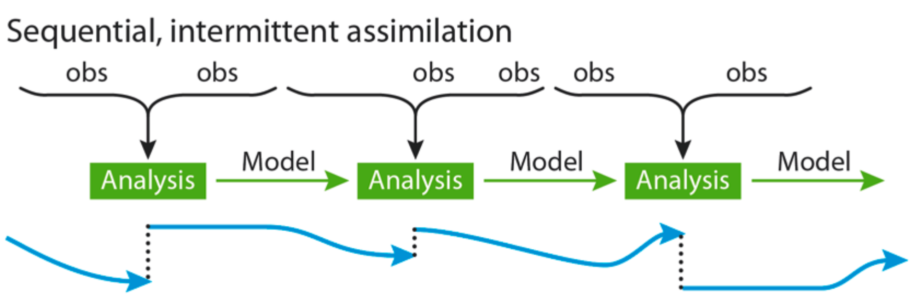
- Systematic approach where a **numerical weather model** is combined with changing weather **observations** (different type/location/time) within a **data assimilation scheme** in a update **cycle**



http://www.oceanwave.jp/etc/movies/anim_wrf-d01.jpg



http://www.ecmwf.int/sites/default/files/obs_inputs.png

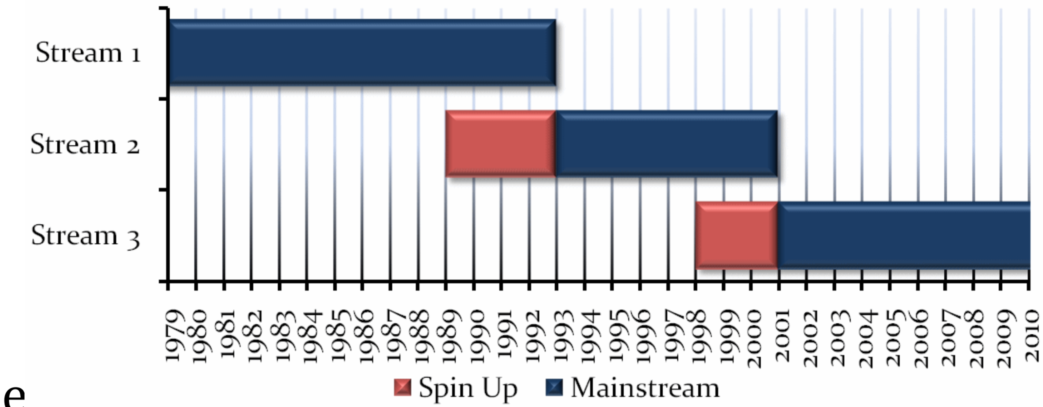


https://climatedataguide.ucar.edu/climate-data/simplistic-overview-reanalysis-data-assimilation-methods

→ **3D** (up to top of atmosphere) **homogeneous consistent estimate of past climate** with high temporal and spatial resolution

MERRA Reanalysis

- **M**odern-**E**ra **R**etrospective analysis for **R**esearch and **A**pplications
- From NASA (National Aeronautics and Space Administration), USA
- **Cycles of 6 hours** since **1979 to present**
- Currently over 1,5 million observations assimilated per cycle. However over **3,5 million ingested** (data thinning and filtering) **worldwide**



http://disc.sci.gsfc.nasa.gov/mdisc/data-holdings/merra-mainstream-and-spinup-data

- Temporal resolution:

Hourly for **surface data**

- Spatial resolution:

0,66° longitude x 0,5° latitude

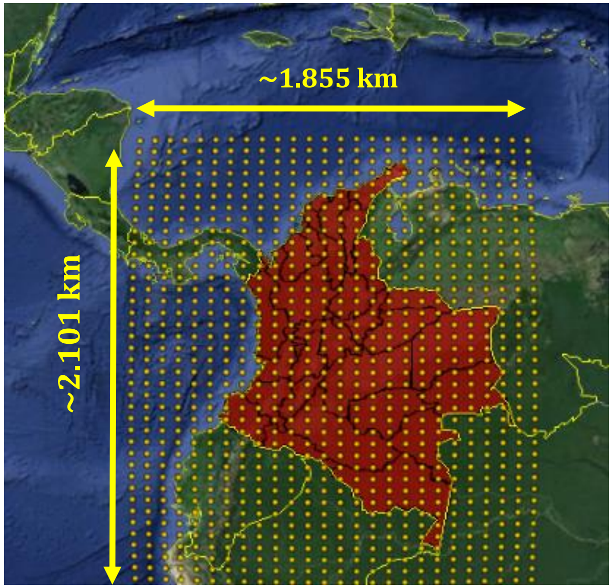
(**~74km x 55km** in Equator)

Data processing

- **1.014 grid points** selected (26 longitudes x 39 latitudes; hourly)

Shaded, not used

Variable	Description	Unit
	Wind resource	
U50M	Eastward wind @ 50m above surface	[m/s]
V50M	Northward wind @ 50m above surface	[m/s]
Z0M	Roughness length, momentum	[m]
RHOA	Surface air density	[kg/m^3]
DISPH	Displacement height	[m]
	Solar resource	
SWGDN	Surface incident shortwave flux	[W/m^2]
T2M	Temperature at 2m above the displacement height	[K]
	Hydro resource	
RUNOFF	Overland runoff	[kg/m^2s]
PRECTOT	Total surface precipitation	[kg/m^2s]
	For checking resolution (constant variable)	
PHIS	Surface geopotential	[m^2/s^2]

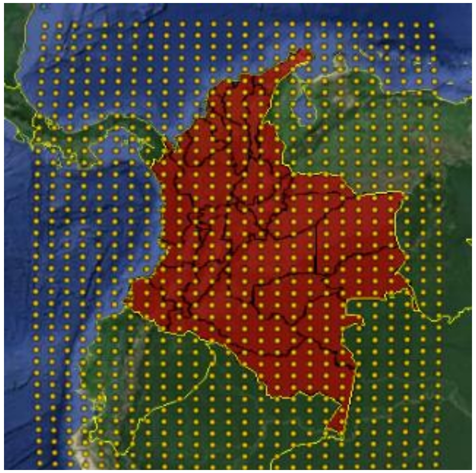


*Own graph in ©Google Earth

- If all years taken, approx. 2,8 x 10^9 data in total…
- Only "Stream 3" taken: **2001 – 2014** (1,1 x 10^9 data processed in ©Matlab)

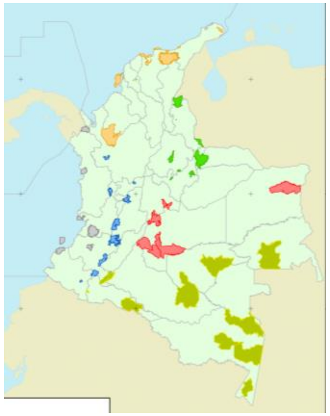
Sites selection

- Highest mean values (wind speed @50m and solar irradiation)
- Location of:
  - Transmission system until 2028
  - Natural national parks
  - Roads network



*Own graph in ©Google Earth

UPME, "Plan De Expansion De Referencia Generacion - Transmisión 2014-2028,"



http://www.parquesnacionales.gov.co/PN N/portel/libreria/php/decide.php?patron =01.040201

©Google Earth

Current hydro power plants (HPP)

- Large (>20MW) ~67% of installed capacity
- Data from **XM** (Power system operator and market administrator in Colombia)
  - 25 HPP → **19 HPP** taken (**24 rivers**)
  - **Rated Capacities**, **location** and **Conversion Factors**
  - **Monthly in-flows** of rivers
  - Different time spans. Mostly **2001-2014**
- **Organization of HPP+rivers**
  - **Generation chains**
    - (UPME, Mining and Energy Planning Unit from Ministry of Energy)
  - **Colombian hydrography**
    - (GIS from SiGaia-private company- and IDEAM -Institute of Hydrology, Meteorology and Environmental Studies-)

A. M. Macias and J. Andrade, "Estudio de generación bajo escenarios de cambio climatico - UPME,"

"Hidrografía de Colombia - IDEAM and SiGaia in ArcGis."

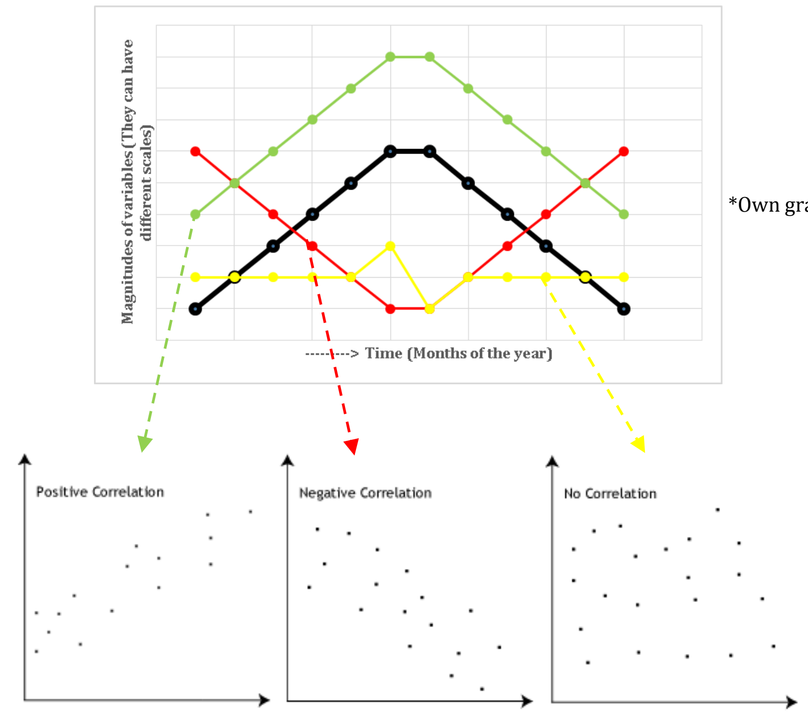
Assessment of energy productions

- **Best scenario** of UPME :1.370MW wind and 239,2MWp solar power in the country until 2028
- For every month (12) of every year between 2001-2014 (14)
  - Wind energy (**99MW wind park for each wind site**)
    - **Hourly wind speeds** @50m extrapolated to **100m** with logarithmic wind profile assuming neutral stratification (**monthly roughness length**; **displacement heights neglected**). Binning of winds speeds (50 of 0,5m/s). Multiplied by bins of Vestas **V126 3,3MW** (Power curve from Notus energy) **Average losses** for a wind park of that size also provided. Density **correction** with **monthly surface air densities**
  - Solar energy (**50MWp PV solar park for each solar site**)
    - **Ostwald´s method**. Most used for estimating PV power with: **hourly irradiations**, **hourly surface temperatures**, temperature **coefficient** and NOCT from Yingli Solar, **PR of 0,82** (optimal system in Colombia, taken from a scientific paper)
  - Hydro energy (**Real Rated Capacities**) (No MERRA data used)
    - In-flows of river(s) x Conversion Factors (limited by Rated Capacities)

Complementarity

- **Pearson´s correlation coefficient (R):** Measures the **strength** and **direction** of linear relationships. Independent of scale of magnitudes

$$R_{xy} = \frac{cov(x,y)}{\sigma_x \sigma_y}$$



*Own graphic

https://statistics.laerd.com/statistical-guides/pearson-correlation-coefficient-statistical-guide.php

- Bet**ween -1 and +1**

+1: Positive: perfectly **dependent**

-1: Negative: perfectly **inverse**

0: no correlated at all

- The **higher the <u>negative</u> R** between x and y, the **more complementary** they are

▬ : Base variable

Complementarity

- From step before → **monthly mean values of resources** organised

- **Intra-annual** (through a year)
  - **Monthly** basis (limited by river in-flows resolution, but good representation due to real variability of in-flows)
  - Hydro-Wind and Hydro-Solar
  - All against all
  - R for every year (14) → **average** of these **Rs** for each pair
- **Inter-annual**
  - **Annual** basis
  - Hydro-Wind and Hydro-Solar
  - All against all
  - **Unique R** for the 14 years for each pair

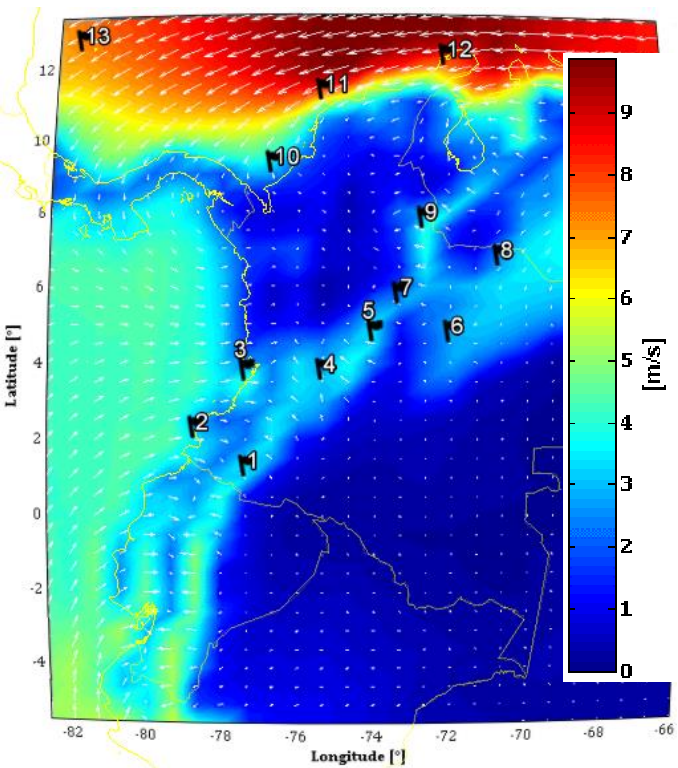
First annual indexes and IAV

- **MERRA-based** wind and solar resource/energy indexes(2001-2014)
  - 100%: average of the mean annual values (wind speed @50, solar insolation)
  - 100%: average of AEPs (Annual Energy Production) wind/solar parks
  - Variation through the 14 years (2001-2014)
  - IAV (Inter-Annual Variability): Standard deviation divided by the "100% value"

- **XM-based** hydro resource/energy indexes (2001-2014)
  - Exactly the same but for mean annual river in-flows and AEP of HPP

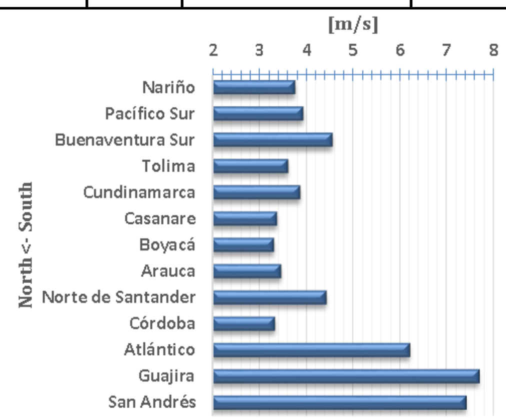
Mean wind speeds @50m

- 13 wind sites



*Own graph. Made in ©Matlab and projected in ©Google Earth

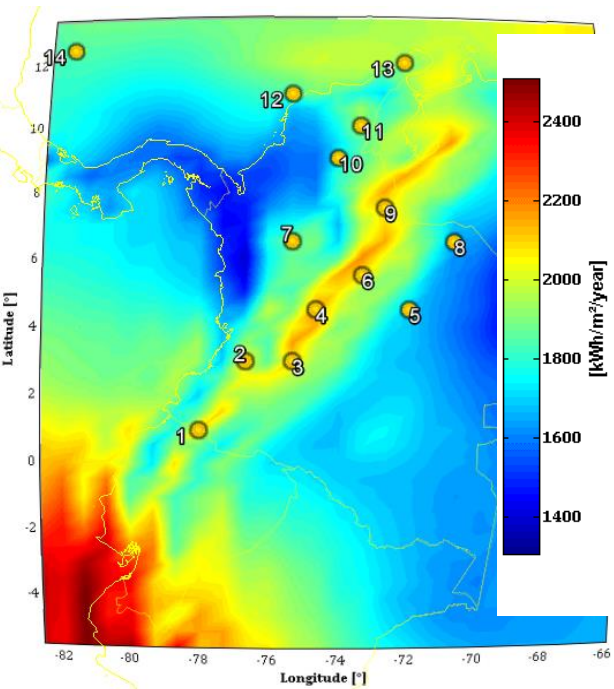
	Name	Long. [°]	Lat. [°]	Mean wind speed @ 50m [m/s]	Mean surface air density [kg/m^3]	Mean roughness length [m]	Height above sea level [m]
1	Nariño	-77,33	+1	3,73	0,923	0,07	2.456
2	Pacífico Sur	-78,66	+2	3,90	1,166	0,03	9
3	Buenaventura Sur	-77,33	+3,5	4,53	1,156	0,03	101
4	Tolima	-75,33	+3,5	3,58	1,031	0,07	1.230
5	Cundinamarca	-74	+4,5	3,83	0,931	0,07	2.351
6	Casanare	-72	+4,5	3,34	1,146	0,06	165
7	Boyacá	-73,33	+5,5	3,29	0,912	0,19	2.557
8	Arauca	-70,66	+6,5	3,43	1,151	0,06	119
9	Norte de Santander	-72,66	+7,5	4,41	0,973	0,07	1.886
10	Córdoba	-76,66	+9	3,31	1,160	0,29	2
11	Atlántico	-75,33	+11	6,18	1,159	0,20	2
12	Guajira	-72	+12	7,66	1,158	0,05	28
13	San Andrés	-82	+12,5	7,38	1,162	0,07	0



*Own graph

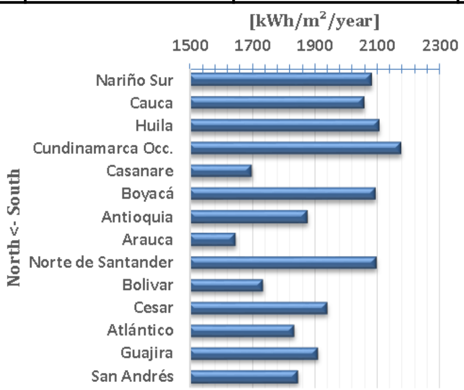
Mean annual solar insolation

- 14 solar sites



*Own graph. Made in ©Matlab and projected in ©Google Earth

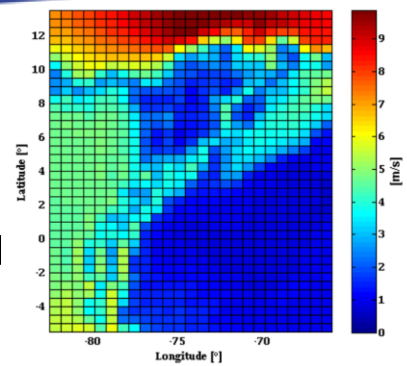
	Name	Long. [°]	Lat. [°]	Mean annual solar surface insolation [kWh/m²/year]	Mean daily solar surface insolation [kWh/m²/day]	Mean temp. [°C]	Mean temp. during day [°C]	Height above sea level [m]
1	Nariño Sur	-78	+1	2.082	5,70	16,34	18,67	2.110
2	Cauca	-76,66	+3	2.057	5,64	19,30	21,46	1.558
3	Huila	-75,33	+3	2.105	5,77	20,25	22,21	1.331
4	Cundinamarca Occidente	-74,66	+4,5	2.175	5,96	22,02	24,26	1.292
5	Casanare	-72	+4,5	1.695	4,64	26,30	27,26	165
6	Boyacá	-73,33	+5,5	2.092	5,73	13,62	15,40	2.557
7	Antioquia	-75,33	+6,5	1.875	5,14	17,64	18,68	1.796
8	Arauca	-70,66	+6,5	1.645	4,51	26,25	27,54	119
9	Norte de Santander	-72,66	+7,5	2.096	5,74	17,10	18,82	1.888
10	Bolivar	-74	+9	1.733	4,75	26,94	27,64	128
11	Cesar	-73,33	+10	1.939	5,31	24,36	26,14	603
12	Atlántico	-75,33	+11	1.833	5,02	28,08	28,53	2
13	Guajira	-72	+12	1.908	5,23	27,62	29,23	28
14	San Andrés	-82	12,5	1.845	5,05	27,87	27,90	0

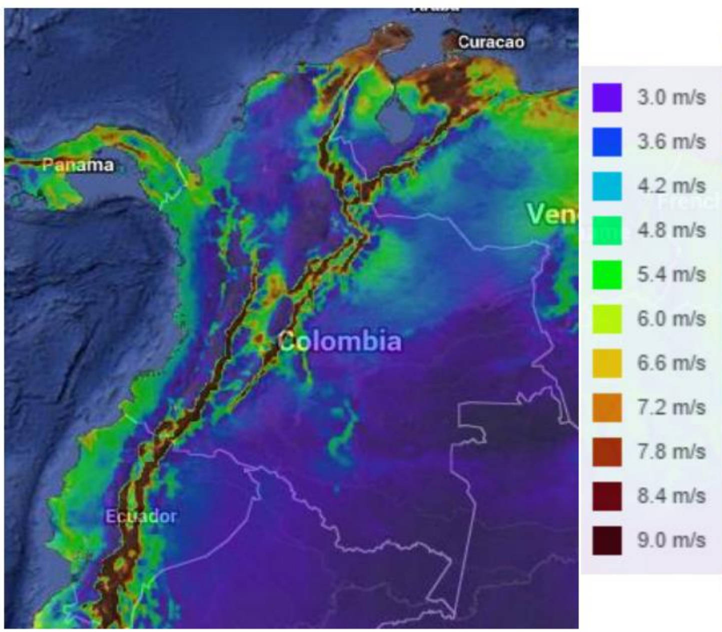


*Own graph

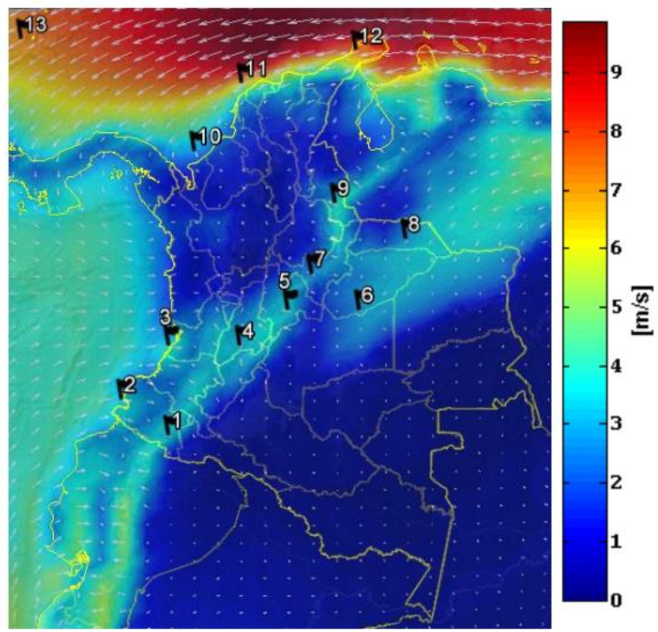
Mean wind resource

Interpolation in ©Matlab only for visual purposes

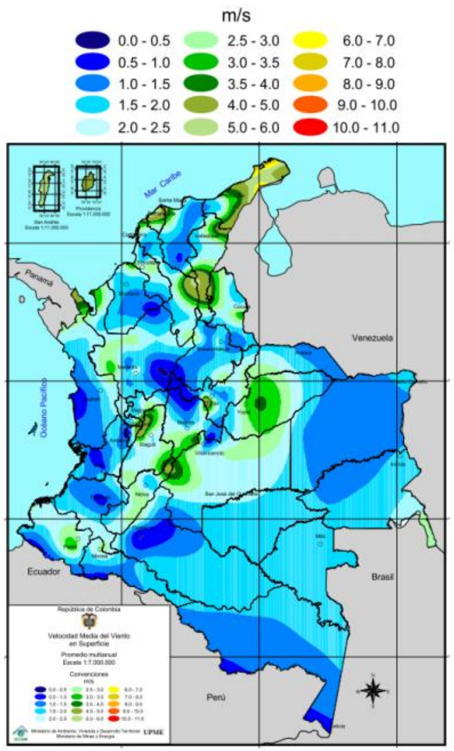




@80m
IRENA Global Atlas
Mesoscale
5km resolution



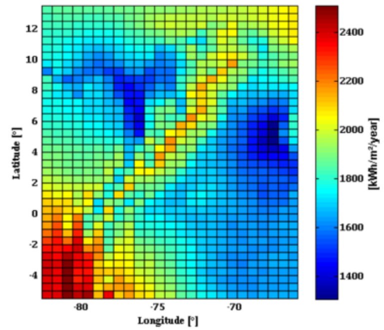
@50m
MERRA
Reanalysis
~74km x 55km resolution

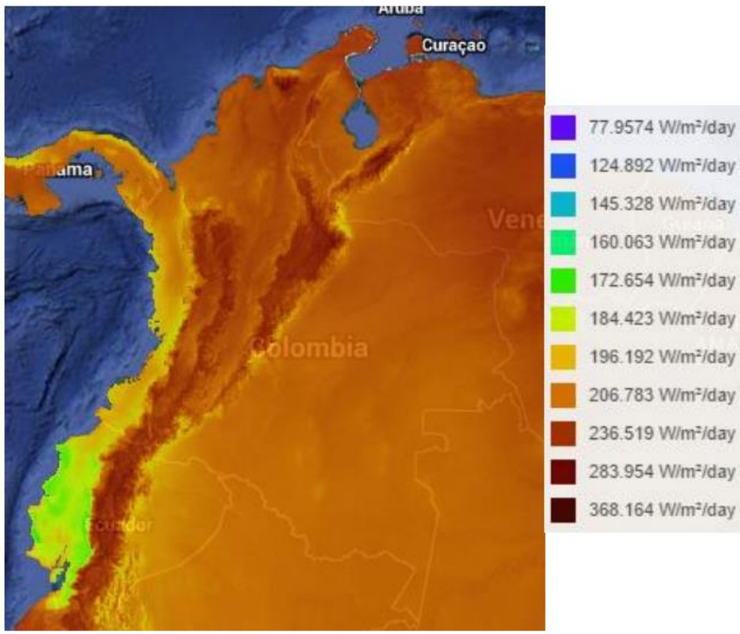


@10m
UPME/IDEAM Atlas 2005
Mesoscale+Measurements
10km resolution

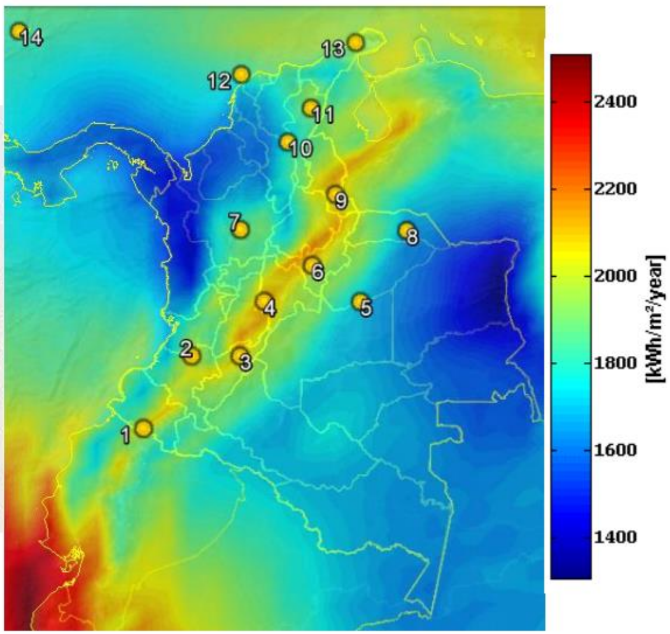
Mean solar resource

Interpolation in ©Matlab only for visual purposes

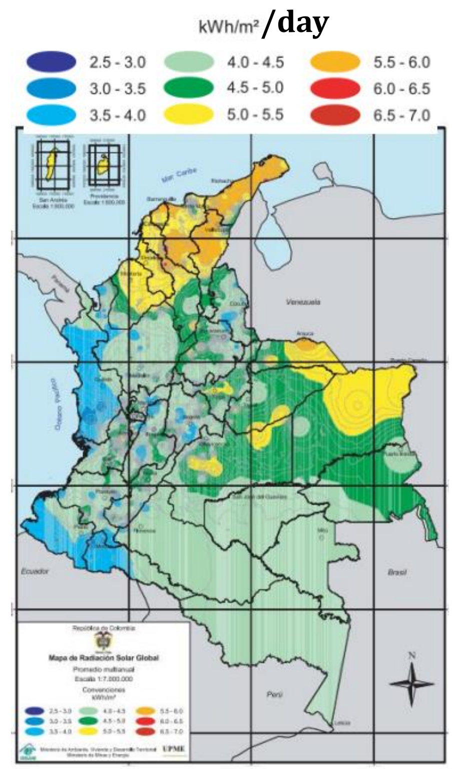




Irradiation
IRENA Global Atlas
Mesoscale
5km resolution



Annual insolation
MERRA
Reanalysis
~74km x 55km resolution



Daily insolation
UPME/IDEAM Atlas 2005
Mesoscale+Measurements
10km resolution

International case studies

- Studies comparing measurements with Reanalysis (including MERRA):
  - Accuracy of **magnitudes** very much **site-dependent**
  - Better for fairly flat areas over large areas (e.g. coastal areas, offshore)
  - **Complex terrains** (e.g. steep shorelines, mountains) **strong positive or negative biases**
  - Negative/positive t**rends** during the time observed (also observed here!)
  - **However**, several R found >0,75. Time variations captured good → purpose of this study! Again, not everywhere

→**Surface smoothing** does not reproduce enhancement/weakening of resource thanks to **topography** and **local thermal circulations** (e.g. land-sea and mountain-valley breezes) having an **impact** in wind flows, cloud dynamics, aerosol and gas transport, etc… specially in complex terrains

→Change in **quantity of observations** taken through time

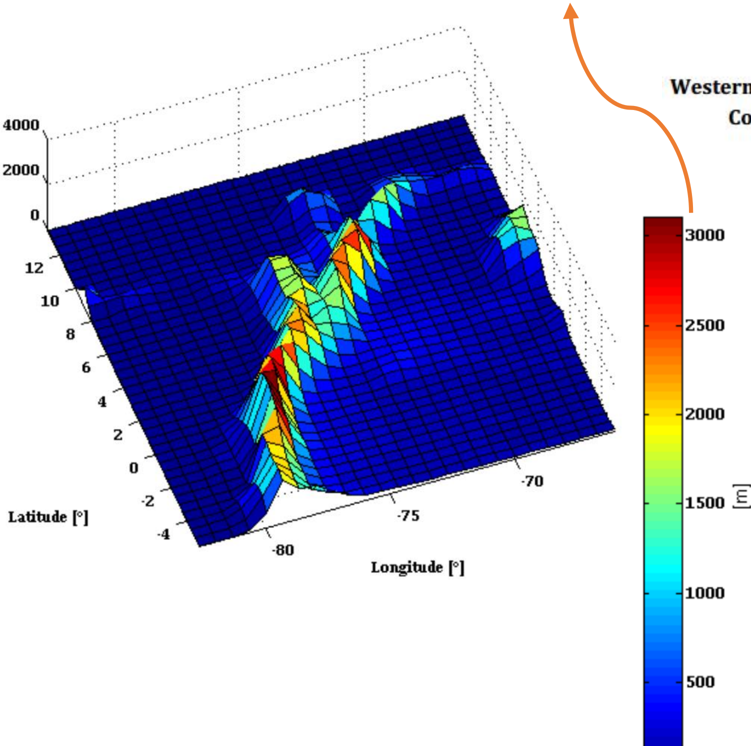
→**Location of observations**

Due to **resource-to-energy sensitivities**, assessed **AEPs** high uncertainties and **likely to strong underestimations** in the **Andes** (heights over 5.000m), especially for wind power. Thus, results **focused** in meteorological **resources** (though energy results are in the final document)

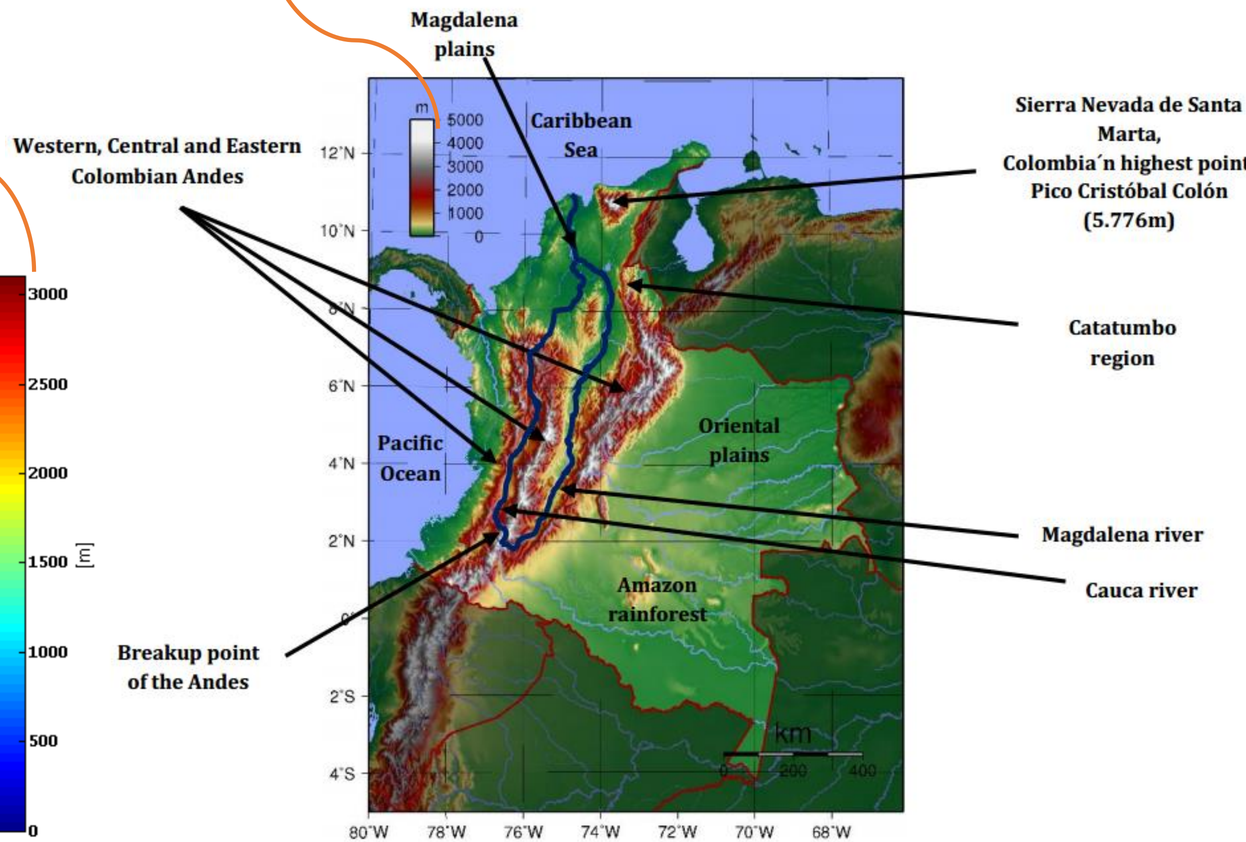
Surface smoothing

3.000m

5.000m



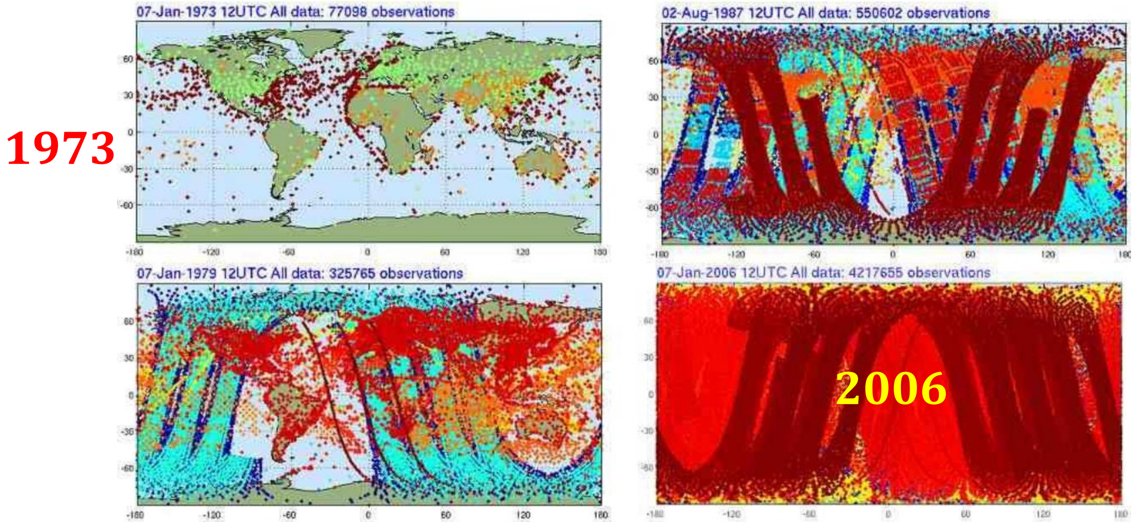
*Own graph. Made in ©Matlab



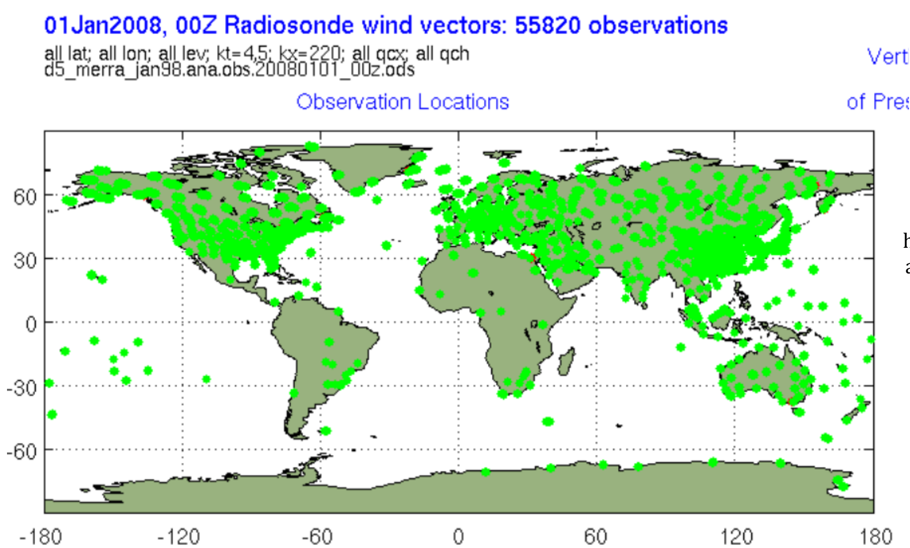
https://upload.wikimedia.org/wikipedia/commons/2/2c/Colombia_Topography_2.png

- “Two Andes Cordilleras from three”

Observations



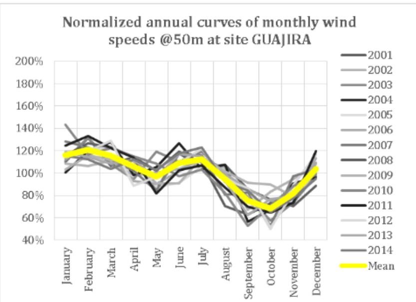
http://earthzine.org/2008/09/26/nasas-modern-era-retrospective-analysis/

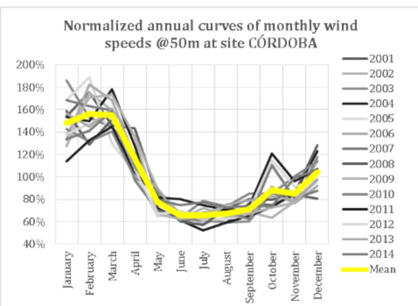


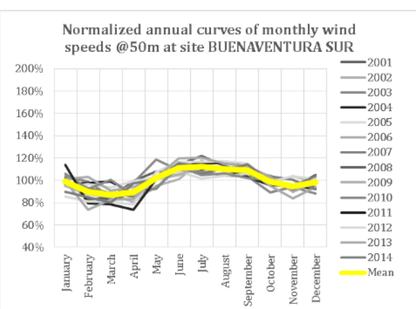
http://gmao.gsfc.nasa.gov/research/merra/catalog/

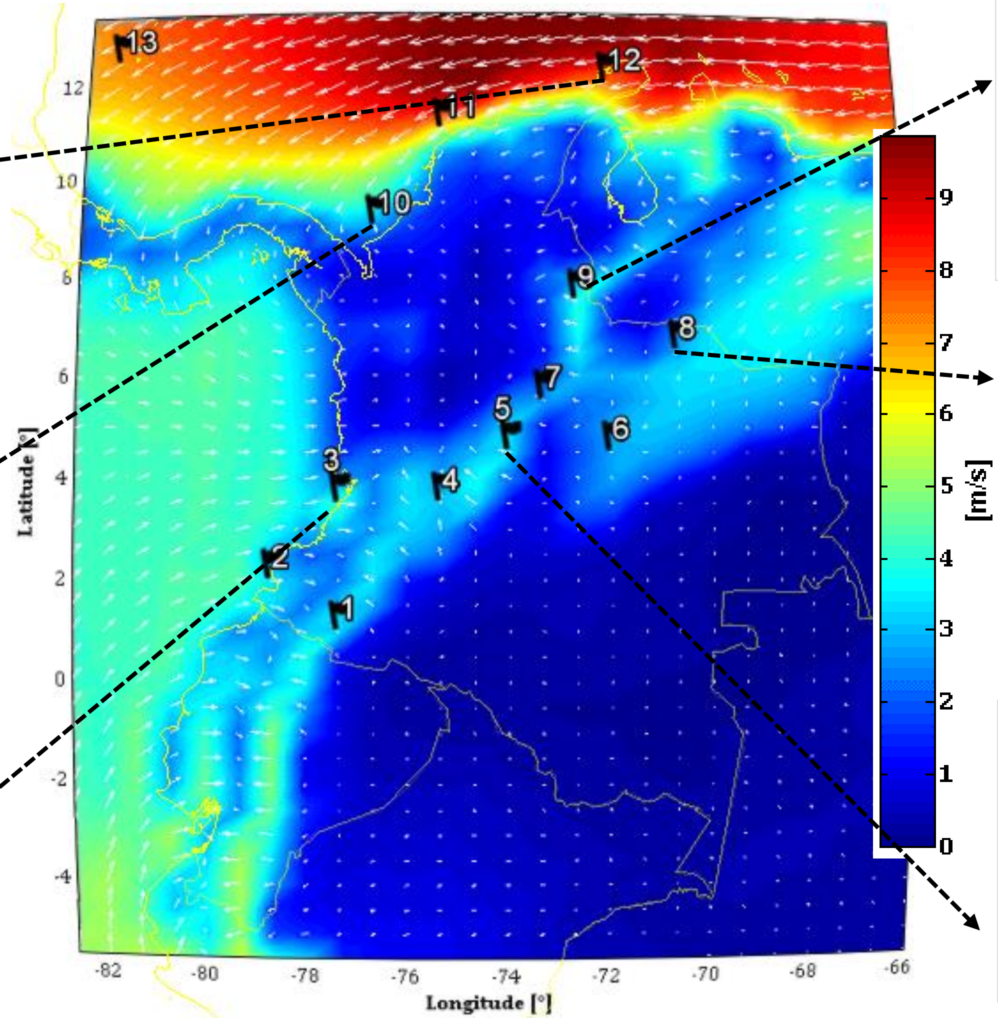
Monthly patterns wind speeds @50m

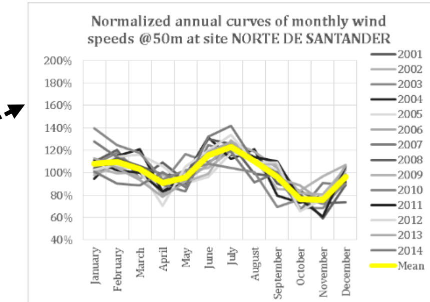
- 13 wind sites

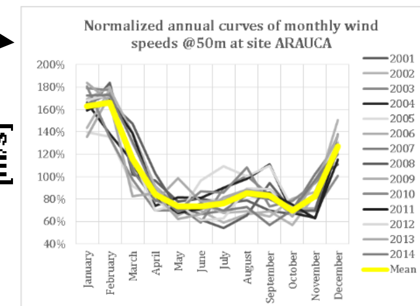


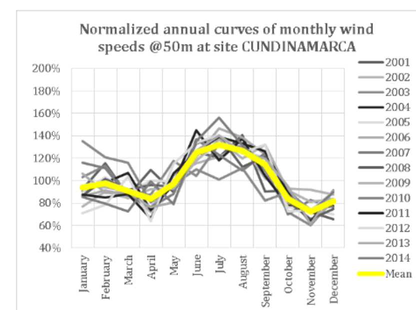








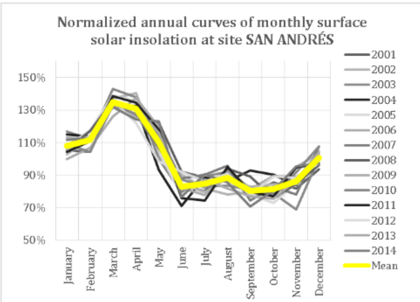


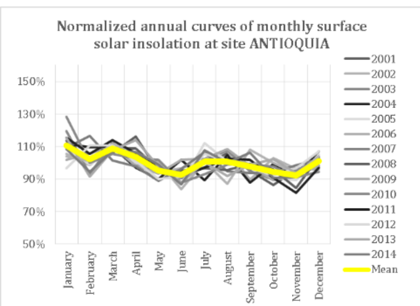


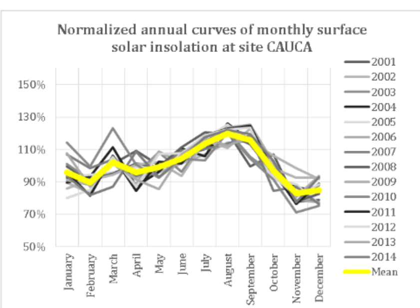
*Own graphs. Made in ©Matlab and projected in ©Google Earth

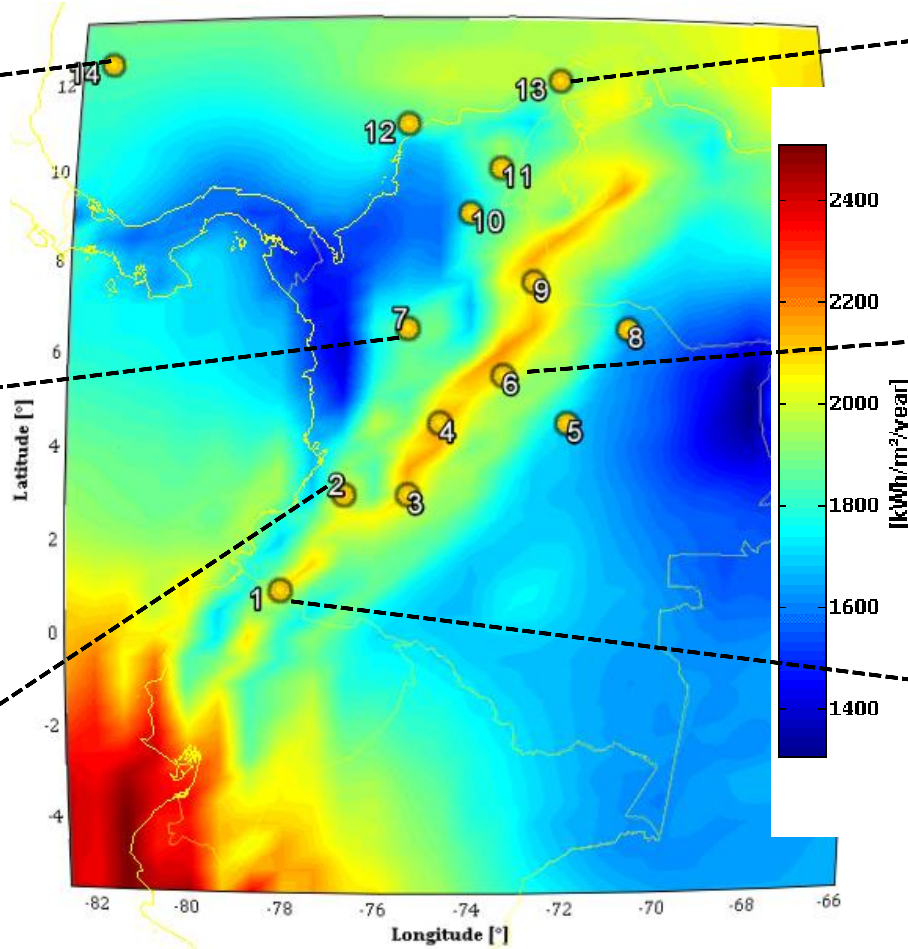
Monthly patterns solar insolation

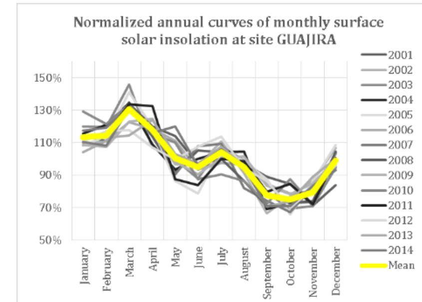
- 14 solar sites

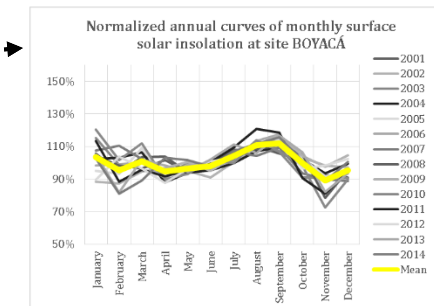


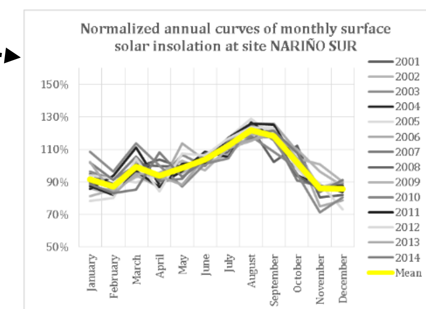












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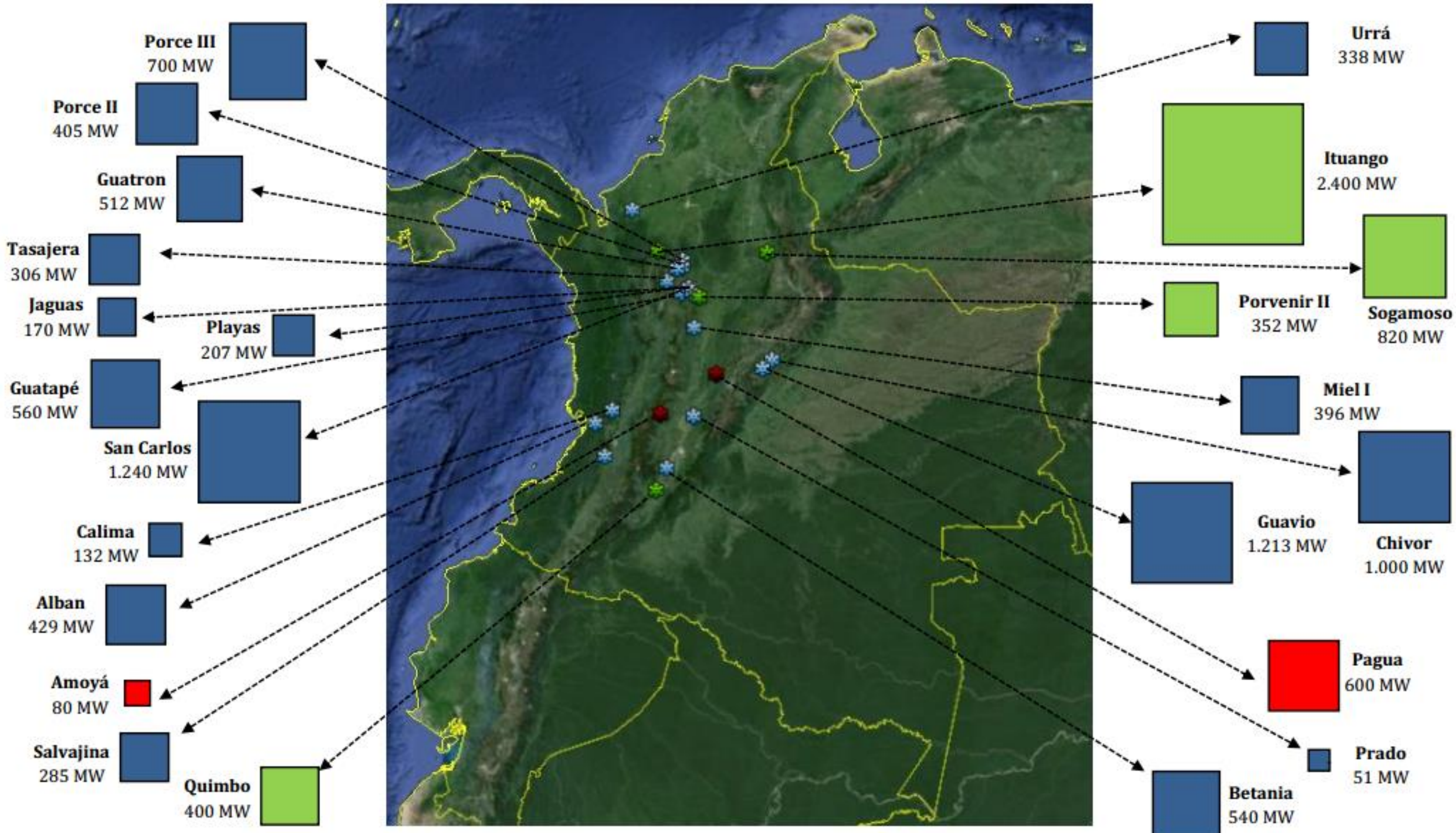
Hydro Power Plants

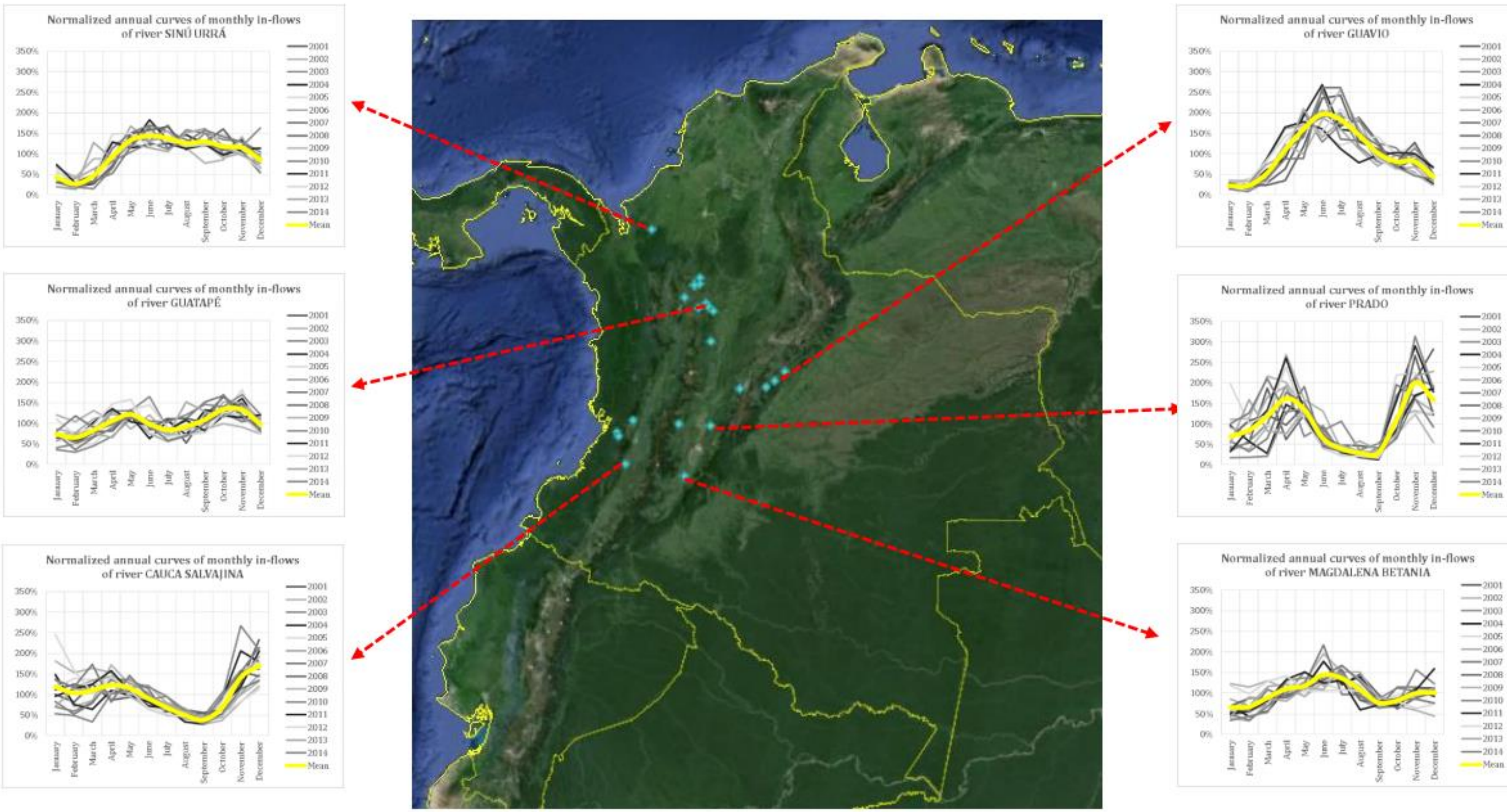
19 current large HPP (blue with dam, red run-of-the-river) + 4 projects(green)



*Own graphs. Projected in ©Google Earth

Hydro Power Plants

19 current large HPP (blue with dam, red run-of-the-river) + 4 projects(green)



*Own graphs. Projected in ©Google Earth

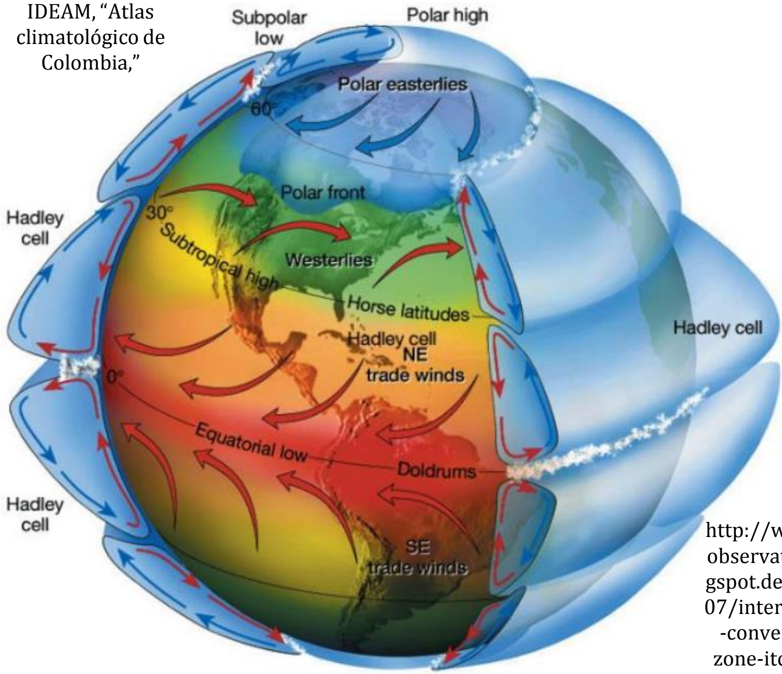
Meteorological dynamics in Colombia

- Global:

Inter-Tropical Convergence Zone **(ITCZ) moving**
Extremes: Dec-Feb South/Jun-Aug North
Hadley cell → Trade winds

- Regional (e.g. far cyclones, others)
- Local (thermal circulations/topography)

IDEAM, "Atlas climatológico de Colombia,"



http://wisdom-observation.blogspot.de/2013/07/intertropical-convergent-zone-itcz.html

ITCZ, general **main driver** for inter-annual mono/bimodal patterns of **wind/solar** values. Several confirmed, previous study.

Precipitations yes, **but not for river in-flows**. More complex dynamics of river in-flows formation (terrain, soils, underground flows) → Taken as a fact from XM

Mean intra-annual (months) R

River in-flows South → North

Wind speeds @50m
North ← South

Wind speeds @50m (North <- South)	River(s) in-flows of hydro power plants (South -> North)																							
	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Nariño	NaN	0,36	-0,62	-0,53	-0,58	0,86	-0,67	0,28	0,64	0,72	-0,74	NaN	-0,10	-0,07	-0,14	0,14	-0,08	0,35	0,01	0,20	NaN	NaN	0,51	0,28
Pacífico Sur	NaN	0,20	-0,39	-0,09	-0,23	0,75	-0,37	0,36	0,46	0,61	-0,33	NaN	0,25	0,24	0,20	0,35	0,25	0,50	0,33	0,36	NaN	NaN	0,61	0,37
Buenaventura Sur	NaN	0,24	-0,53	-0,37	-0,43	0,84	-0,62	0,28	0,54	0,62	-0,58	NaN	0,02	0,04	0,01	0,22	0,03	0,39	0,10	0,30	NaN	NaN	0,53	0,26
Tolima	NaN	0,34	-0,64	-0,48	-0,53	0,83	-0,63	0,31	0,65	0,72	-0,70	NaN	0,01	0,04	-0,04	0,24	-0,01	0,41	0,08	0,24	NaN	NaN	0,57	0,31
Cundinamarca	NaN	0,25	-0,64	-0,66	-0,66	0,80	-0,77	0,12	0,50	0,57	-0,76	NaN	-0,32	-0,28	-0,33	-0,07	-0,29	0,12	-0,20	0,08	NaN	NaN	0,29	0,08
Casanare	NaN	-0,41	0,21	-0,10	-0,03	-0,72	-0,12	-0,55	-0,59	-0,53	0,08	NaN	-0,55	-0,55	-0,50	-0,59	-0,47	-0,59	-0,53	-0,56	NaN	NaN	-0,61	-0,59
Boyacá	NaN	0,28	-0,65	-0,66	-0,67	0,86	-0,75	0,17	0,55	0,62	-0,78	NaN	-0,26	-0,23	-0,28	-0,02	-0,24	0,17	-0,16	0,15	NaN	NaN	0,35	0,13
Arauca	NaN	-0,47	0,26	-0,10	0,00	-0,83	-0,04	-0,64	-0,70	-0,66	0,16	NaN	-0,58	-0,59	-0,54	-0,65	-0,52	-0,69	-0,61	-0,61	NaN	NaN	-0,76	-0,69
Norte de Santander	NaN	0,18	-0,29	-0,65	-0,51	0,59	-0,63	-0,08	0,22	0,23	-0,52	NaN	-0,60	-0,56	-0,54	-0,41	-0,50	-0,27	-0,48	-0,20	NaN	NaN	-0,10	-0,15
Córdoba	NaN	-0,44	0,33	0,02	0,12	-0,85	0,21	-0,55	-0,70	-0,77	0,35	NaN	-0,45	-0,47	-0,42	-0,58	-0,45	-0,72	-0,53	-0,53	NaN	NaN	-0,81	-0,63
Atlántico	NaN	-0,27	0,45	-0,05	0,13	-0,64	0,19	-0,46	-0,59	-0,68	0,33	NaN	-0,58	-0,59	-0,51	-0,69	-0,51	-0,79	-0,62	-0,69	NaN	NaN	-0,80	-0,56
Guajira	NaN	0,13	0,23	-0,34	-0,11	-0,04	-0,15	-0,17	-0,09	-0,19	-0,04	NaN	-0,63	-0,60	-0,54	-0,58	-0,51	-0,57	-0,56	-0,50	NaN	NaN	-0,48	-0,27
San Andrés	NaN	-0,02	0,48	-0,02	0,15	-0,17	0,15	-0,18	-0,33	-0,37	0,34	NaN	-0,50	-0,50	-0,40	-0,60	-0,36	-0,61	-0,45	-0,58	NaN	NaN	-0,52	-0,27

*Own graph

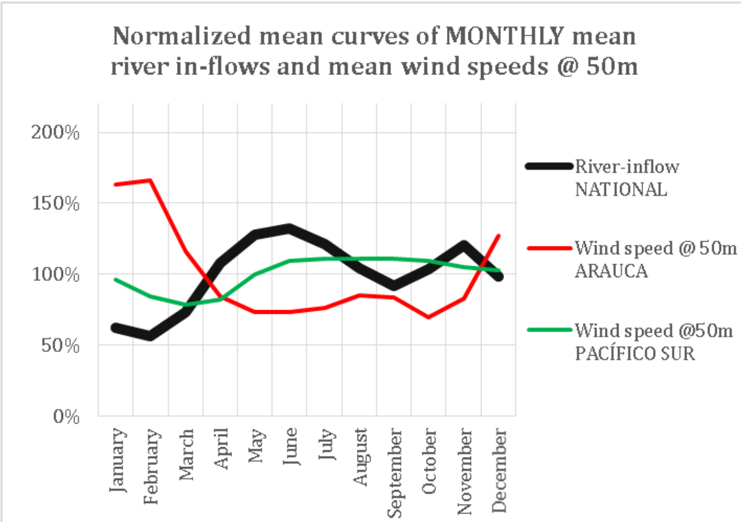
River in-flows South → North

Solar insolation
North ← South

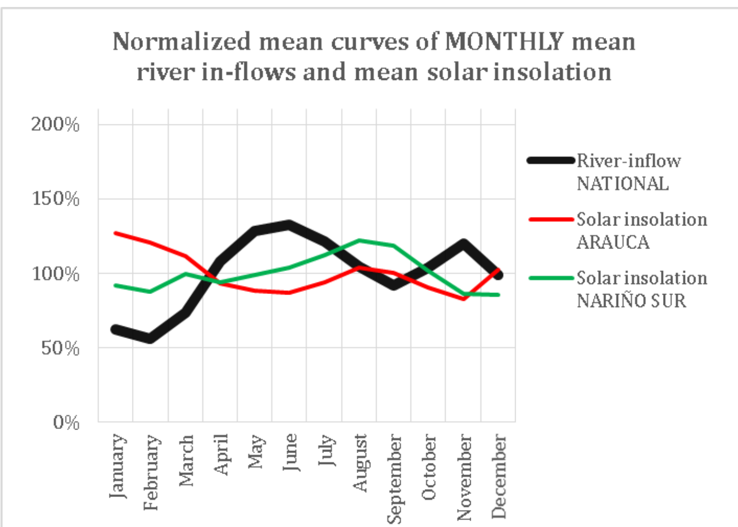
Solar insolation (North <- South)	River(s) in-flows of hydro power plants (South -> North)																							
	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Nariño Sur	NaN	0,06	-0,82	-0,56	-0,67	0,71	-0,72	0,07	0,43	0,53	-0,77	NaN	-0,08	-0,06	-0,16	0,15	-0,18	0,26	-0,06	0,25	NaN	NaN	0,40	0,05
Cauca	NaN	0,08	-0,78	-0,65	-0,69	0,69	-0,75	0,01	0,40	0,47	-0,78	NaN	-0,20	-0,18	-0,27	0,03	-0,30	0,13	-0,19	0,09	NaN	NaN	0,29	-0,01
Huila	NaN	-0,03	-0,82	-0,56	-0,64	0,67	-0,71	0,00	0,36	0,44	-0,75	NaN	-0,08	-0,05	-0,15	0,15	-0,19	0,23	-0,08	0,20	NaN	NaN	0,37	-0,01
inamarca Occidente	NaN	0,02	-0,77	-0,70	-0,73	0,76	-0,82	-0,06	0,35	0,43	-0,81	NaN	-0,32	-0,28	-0,36	-0,06	-0,39	0,05	-0,28	0,02	NaN	NaN	0,22	-0,09
Casanare	NaN	-0,41	-0,26	-0,41	-0,39	-0,36	-0,44	-0,49	-0,37	-0,25	-0,34	NaN	-0,62	-0,61	-0,62	-0,55	-0,60	-0,51	-0,60	-0,54	NaN	NaN	-0,43	-0,60
Boyacá	NaN	-0,35	-0,73	-0,64	-0,68	0,57	-0,76	-0,36	-0,03	0,10	-0,71	NaN	-0,39	-0,38	-0,45	-0,20	-0,48	-0,14	-0,39	-0,04	NaN	NaN	0,01	-0,39
Antioquia	NaN	-0,34	0,00	-0,36	-0,23	-0,39	-0,18	-0,49	-0,44	-0,45	-0,14	NaN	-0,69	-0,70	-0,64	-0,72	-0,63	-0,72	-0,70	-0,62	NaN	NaN	-0,62	-0,62
Arauca	NaN	-0,47	0,00	-0,33	-0,24	-0,78	-0,24	-0,64	-0,59	-0,52	-0,09	NaN	-0,66	-0,65	-0,64	-0,65	-0,64	-0,68	-0,69	-0,63	NaN	NaN	-0,71	-0,73
Norte de Santander	NaN	0,00	-0,69	-0,66	-0,70	0,61	-0,72	-0,09	0,28	0,38	-0,77	NaN	-0,30	-0,28	-0,34	-0,09	-0,37	0,02	-0,29	-0,02	NaN	NaN	0,19	-0,11
Bolivar	NaN	-0,19	0,25	-0,28	-0,12	-0,44	-0,09	-0,42	-0,44	-0,45	0,05	NaN	-0,69	-0,68	-0,61	-0,71	-0,56	-0,72	-0,64	-0,64	NaN	NaN	-0,72	-0,53
Cesar	NaN	-0,14	0,15	-0,39	-0,22	-0,31	-0,19	-0,42	-0,36	-0,37	-0,08	NaN	-0,72	-0,71	-0,65	-0,71	-0,61	-0,70	-0,69	-0,62	NaN	NaN	-0,67	-0,52
Atlántico	NaN	-0,15	0,39	-0,12	0,09	-0,54	0,17	-0,36	-0,43	-0,56	0,20	NaN	-0,55	-0,55	-0,48	-0,63	-0,46	-0,71	-0,56	-0,53	NaN	NaN	-0,73	-0,46
Guajira	NaN	-0,05	0,25	-0,26	-0,04	-0,42	0,03	-0,29	-0,25	-0,40	0,03	NaN	-0,55	-0,53	-0,48	-0,55	-0,46	-0,61	-0,55	-0,42	NaN	NaN	-0,60	-0,38
San Andrés	NaN	-0,17	0,37	0,02	0,20	-0,72	0,32	-0,29	-0,39	-0,58	0,25	NaN	-0,29	-0,29	-0,25	-0,38	-0,29	-0,54	-0,38	-0,36	NaN	NaN	-0,62	-0,38

*Own graph

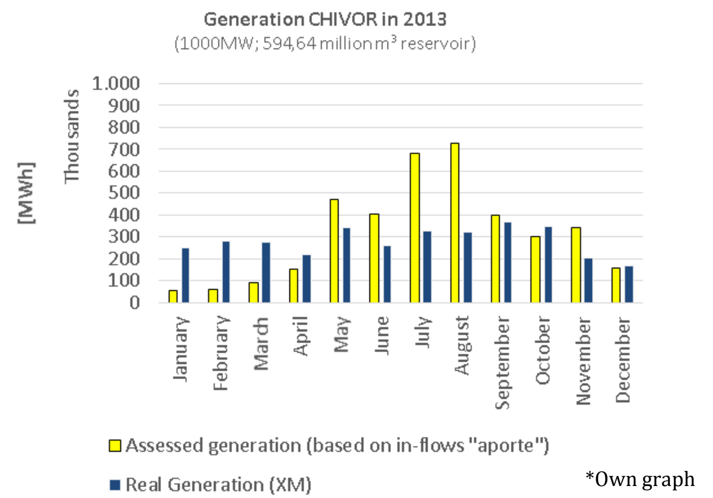
Mean intra-annual (months) R



*Own graph



*Own graph



*Own graph

**Example of monthly patterns of energy production based on in-flows different to real generation reported.
→Causes: Reservoirs and operations based on market strategies. Seen in other studies.
Out of scope. However, in-flows represent the real hydrology

Unique inter-annual (years) R

River in-flows South → North

Wind speeds @50m North ← South

Wind speeds @50m (North <- South)	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
	River(s) in-flows of hydro power plants (South -> North)																							
Nariño	NaN	-0,36	-0,54	-0,21	-0,41	NaN	-0,67	-0,49	0,63	0,27	-0,47	NaN	-0,79	-0,80	-0,73	-0,80	-0,76	-0,44	-0,67	-0,76	NaN	NaN	-0,45	-0,55
Pacífico Sur	NaN	-0,48	-0,40	0,30	-0,27	NaN	-0,40	-0,62	-0,31	-0,71	-0,16	NaN	-0,44	-0,50	-0,50	-0,44	-0,44	-0,06	-0,41	-0,69	NaN	NaN	0,22	-0,46
Buenaventura Sur	NaN	-0,38	-0,39	-0,03	-0,33	NaN	-0,55	-0,84	-0,14	-0,71	-0,02	NaN	-0,50	-0,55	-0,58	-0,42	-0,52	-0,17	-0,44	-0,91	NaN	NaN	-0,03	-0,50
Tolima	NaN	-0,51	-0,70	-0,32	-0,52	NaN	-0,79	-0,62	0,43	0,05	-0,54	NaN	-0,84	-0,86	-0,84	-0,78	-0,84	-0,46	-0,76	-0,80	NaN	NaN	-0,41	-0,74
Cundinamarca	NaN	-0,37	-0,64	-0,36	-0,62	NaN	-0,74	-0,70	0,53	-0,04	-0,41	NaN	-0,87	-0,88	-0,85	-0,80	-0,84	-0,57	-0,82	-0,89	NaN	NaN	-0,47	-0,67
Casanare	NaN	-0,09	-0,20	0,11	-0,13	NaN	-0,43	-0,28	0,59	0,43	-0,26	NaN	-0,42	-0,43	-0,27	-0,68	-0,46	-0,34	-0,35	0,60	NaN	NaN	-0,18	-0,24
Boyacá	NaN	-0,33	-0,59	-0,38	-0,57	NaN	-0,73	-0,71	0,52	-0,04	-0,31	NaN	-0,84	-0,86	-0,82	-0,79	-0,82	-0,57	-0,78	-0,88	NaN	NaN	-0,46	-0,64
Arauca	NaN	0,16	-0,04	0,12	-0,04	NaN	-0,30	-0,39	0,58	0,25	-0,15	NaN	-0,28	-0,33	-0,23	-0,45	-0,44	-0,42	-0,35	-1,00	NaN	NaN	-0,29	-0,15
Norte de Santander	NaN	-0,33	-0,61	-0,38	-0,63	NaN	-0,66	-0,67	0,45	-0,15	-0,38	NaN	-0,77	-0,77	-0,77	-0,64	-0,72	-0,54	-0,73	-0,98	NaN	NaN	-0,39	-0,60
Córdoba	NaN	-0,41	-0,05	-0,29	0,11	NaN	-0,20	-0,29	-0,06	-0,14	0,33	NaN	-0,20	-0,08	-0,01	-0,08	0,01	0,02	0,17	0,70	NaN	NaN	0,10	-0,17
Atlántico	NaN	-0,13	-0,36	-0,39	-0,40	NaN	-0,48	-0,58	0,49	-0,04	-0,14	NaN	-0,52	-0,50	-0,49	-0,39	-0,50	-0,46	-0,44	-0,98	NaN	NaN	-0,39	-0,37
Guajira	NaN	-0,29	-0,59	-0,33	-0,66	NaN	-0,52	-0,57	0,45	-0,18	-0,54	NaN	-0,67	-0,68	-0,73	-0,48	-0,68	-0,53	-0,72	-0,95	NaN	NaN	-0,48	-0,56
San Andrés	NaN	-0,27	-0,53	-0,66	-0,63	NaN	-0,50	-0,47	0,53	-0,05	-0,30	NaN	-0,60	-0,57	-0,62	-0,35	-0,55	-0,50	-0,56	-0,77	NaN	NaN	-0,63	-0,51

*Own graph

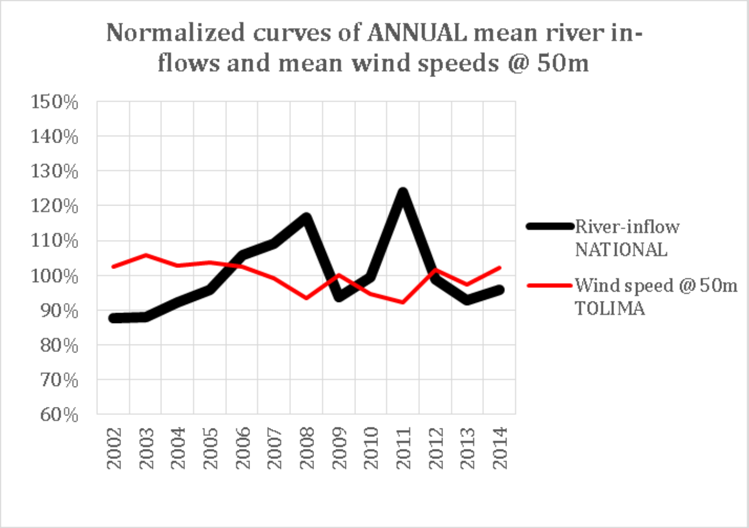
River in-flows South → North

Solar insolation North ← South

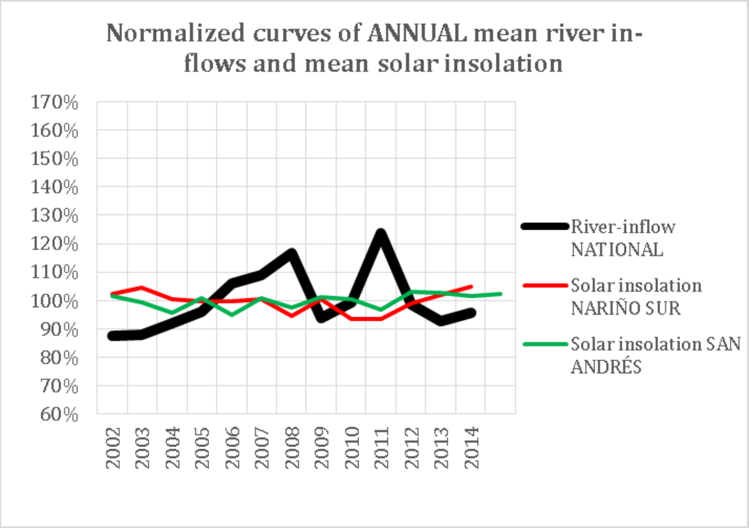
Solar insolation (North <- South)	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
	River(s) in-flows of hydro power plants (South -> North)																							
Nariño Sur	NaN	-0,50	-0,74	-0,13	-0,66	NaN	-0,72	-0,72	0,33	-0,26	-0,68	NaN	-0,82	-0,87	-0,90	-0,74	-0,87	-0,48	-0,87	-0,96	NaN	NaN	-0,37	-0,74
Cauca	NaN	-0,42	-0,59	-0,14	-0,52	NaN	-0,74	-0,72	0,39	-0,08	-0,39	NaN	-0,84	-0,85	-0,81	-0,79	-0,76	-0,37	-0,73	-0,90	NaN	NaN	-0,25	-0,61
Huila	NaN	-0,52	-0,65	-0,11	-0,47	NaN	-0,79	-0,82	0,16	-0,30	-0,34	NaN	-0,85	-0,87	-0,86	-0,78	-0,78	-0,33	-0,72	-0,95	NaN	NaN	-0,11	-0,69
inamarca Occidente	NaN	-0,42	-0,49	-0,19	-0,38	NaN	-0,72	-0,68	0,39	0,03	-0,21	NaN	-0,80	-0,76	-0,69	-0,75	-0,66	-0,34	-0,56	-0,82	NaN	NaN	-0,16	-0,53
Casanare	NaN	-0,23	-0,42	0,14	-0,41	NaN	-0,53	-0,47	0,42	0,04	-0,46	NaN	-0,63	-0,67	-0,64	-0,65	-0,64	-0,39	-0,63	-0,82	NaN	NaN	-0,20	-0,44
Boyacá	NaN	-0,50	-0,61	-0,27	-0,57	NaN	-0,80	-0,78	0,20	-0,22	-0,22	NaN	-0,81	-0,77	-0,73	-0,68	-0,63	-0,31	-0,60	-0,90	NaN	NaN	-0,01	-0,61
Antioquia	NaN	-0,22	-0,29	-0,08	-0,19	NaN	-0,55	-0,50	0,52	0,24	-0,11	NaN	-0,62	-0,60	-0,48	-0,68	-0,51	-0,28	-0,38	-0,82	NaN	NaN	-0,16	-0,30
Arauca	NaN	0,35	0,16	0,31	0,04	NaN	0,06	-0,03	0,34	0,11	-0,26	NaN	0,13	0,03	0,01	0,02	-0,15	-0,28	-0,22	-0,88	NaN	NaN	-0,32	0,00
Norte de Santander	NaN	-0,25	-0,40	-0,27	-0,52	NaN	-0,56	-0,61	0,13	-0,27	-0,05	NaN	-0,55	-0,52	-0,54	-0,35	-0,40	-0,22	-0,42	-0,82	NaN	NaN	-0,01	-0,32
Bolivar	NaN	0,30	0,05	-0,11	-0,13	NaN	-0,15	-0,19	0,67	0,36	0,19	NaN	-0,30	-0,32	-0,24	-0,39	-0,31	-0,42	-0,31	-0,26	NaN	NaN	-0,40	-0,02
Cesar	NaN	0,25	-0,06	-0,13	-0,28	NaN	-0,19	-0,33	0,58	0,08	0,06	NaN	-0,34	-0,39	-0,36	-0,37	-0,46	-0,56	-0,47	-0,75	NaN	NaN	-0,48	-0,15
Atlántico	NaN	0,33	0,07	-0,22	-0,23	NaN	0,08	-0,16	0,37	-0,10	0,28	NaN	-0,11	-0,14	-0,17	-0,02	-0,21	-0,45	-0,28	-0,71	NaN	NaN	-0,45	0,01
Guajira	NaN	0,17	-0,16	-0,15	-0,36	NaN	-0,14	-0,36	0,43	-0,12	-0,14	NaN	-0,31	-0,37	-0,41	-0,25	-0,50	-0,57	-0,53	-0,88	NaN	NaN	-0,51	-0,21
San Andrés	NaN	0,45	0,18	-0,17	-0,09	NaN	0,35	0,38	0,40	0,33	-0,08	NaN	0,30	0,27	0,21	0,32	0,18	-0,06	0,10	0,92	NaN	NaN	-0,46	0,36

*Own graph

Unique inter-annual (years) R



*Own graph



*Own graph

Annual MERRA and XM resource indexes

Wind (2,9%<IAV>8,5%). Confirmed by other studies (higher in inter-tropics)

North <- South	Mean wind speed @50m [m/s]	MERRA-based wind resource index														IAV
	100%	2001	2002	20[illegible]3	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
Nariño	3,73	107%	109%	11[illegible]%	107%	106%	109%	98%	92%	93%	85%	87%	101%	93%	104%	8,4%
Pacífico Sur	3,90	102%	100%	103[illegible]	99%	102%	97%	104%	97%	100%	101%	96%	95%	103%	104%	2,9%
Buenaventura Sur	4,53	103%	99%	100[illegible]	100%	102%	97%	104%	99%	103%	99%	94%	97%	101%	104%	2,9%
Tolima	3,58	102%	103%	106[illegible]	103%	104%	103%	99%	93%	100%	95%	92%	102%	97%	102%	4,0%
Cundinamarca	3,83	107%	110%	103[illegible]	103%	102%	103%	100%	93%	103%	87%	88%	99%	97%	106%	6,6%
Casanare	3,34	100%	106%	102[illegible]	108%	106%	100%	105%	98%	95%	90%	98%	98%	97%	97%	4,7%
Boyacá	3,29	106%	110%	102[illegible]	103%	103%	103%	100%	94%	103%	87%	88%	99%	96%	105%	6,3%
Arauca	3,43	99%	104%	100[illegible]	106%	103%	101%	104%	105%	98%	86%	94%	99%	100%	101%	4,9%
Norte de Santander	4,41	109%	114%	100[illegible]	102%	95%	102%	100%	96%	105%	87%	87%	98%	101%	105%	7,2%
Córdoba	3,31	103%	103%	99[illegible]	108%	104%	98%	98%	103%	103%	106%	96%	92%	94%	93%	4,8%
Atlántico	6,18	105%	111%	96[illegible]	108%	93%	101%	101%	103%	108%	87%	89%	97%	99%	101%	6,7%
Guajira	7,66	110%	112%	10[illegible]%	102%	88%	101%	97%	96%	107%	84%	88%	98%	104%	111%	8,5%
San Andrés	7,38	106%	109%	9[illegible]%	106%	92%	100%	95%	98%	107%	94%	92%	101%	97%	106%	5,7%

*Own graph

Solar (2,0%<IAV>6,5%)

North <- South	Mean annual solar surface insolation [kWh/m²/year]	MERRA-based solar resource index														IAV
	100%	2001	2002	2[illegible]03	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
Nariño Sur	2.082	104%	102%	10[illegible]%	101%	100%	100%	100%	95%	101%	94%	93%	99%	102%	105%	3,6%
Cauca	2.057	107%	106%	10[illegible]%	101%	102%	102%	102%	96%	99%	91%	92%	97%	98%	103%	4,8%
Huila	2.105	104%	103%	105[illegible]	100%	102%	102%	103%	95%	101%	95%	91%	97%	99%	103%	3,8%
Cundinamarca Occ.	2.175	108%	109%	107[illegible]	103%	105%	103%	102%	98%	98%	90%	89%	96%	93%	99%	6,2%
Casanare	1.695	102%	104%	107[illegible]	99%	101%	100%	102%	99%	96%	93%	95%	100%	99%	104%	3,7%
Boyacá	2.092	106%	107%	103[illegible]	100%	101%	98%	103%	98%	102%	95%	93%	99%	97%	99%	3,8%
Antioquia	1.875	107%	109%	103[illegible]	105%	104%	105%	102%	101%	96%	89%	92%	96%	94%	97%	5,7%
Arauca	1.645	96%	100%	101[illegible]	100%	99%	98%	102%	104%	97%	95%	98%	103%	102%	106%	3,1%
Norte de Santander	2.096	104%	103%	100[illegible]	98%	99%	99%	101%	101%	101%	97%	97%	101%	100%	100%	2,0%
Bolivar	1.733	100%	107%	98[illegible]	102%	100%	103%	101%	104%	99%	91%	98%	99%	95%	104%	3,9%
Cesar	1.939	100%	105%	97[illegible]	100%	100%	101%	100%	103%	101%	92%	97%	100%	99%	105%	3,2%
Atlántico	1.833	101%	105%	94[illegible]	98%	97%	100%	98%	106%	103%	93%	98%	99%	101%	108%	4,3%
Guajira	1.908	101%	102%	98[illegible]	100%	98%	101%	98%	102%	103%	91%	97%	99%	103%	107%	3,6%
San Andrés	1.845	102%	99%	9[illegible]%	101%	95%	101%	98%	101%	101%	97%	103%	103%	102%	102%	2,5%

*Own graph

Hydro (8,2%<IAV>43,7%)

North <- South	Mean in-flow [m³/s]	XM-based hydro resource index														IAV
	100[illegible]	2001	2002	20[illegible]	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
Magdalena Betania	4[illegible],6	83%	92%	79%	90%	98%	112%	112%	119%	99%	85%	127%	105%	92%	108%	13,8%
Cauca Salvajina	[illegible]7,4	78%	74%	76%	[illegible]9%	105%	111%	116%	147%	91%	102%	140%	89%	82%	101%	21,8%
Alto Anchicayá	46,1	97%	86%	107%	[illegible]%	102%	102%	111%	107%	88%	107%	110%	89%	105%	95%	8,2%
Digua	28,9	92%	104%	105%	9[illegible]%	96%	99%	120%	101%	91%	80%	106%	95%	108%	110%	9,4%
Calim[illegible]	11,7	73%	61%	88%	10[illegible]%	104%	132%	126%	140%	84%	117%	117%	83%	88%	87%	22,7%
Amoy[illegible]	15,3														100%	0,0%
Pra[illegible]	57,1	64%	71%	76%	80[illegible]	92%	109%	87%	146%	93%	112%	178%	80%	100%	112%	29,7%
Bogotá N[illegible]	30,9	45%	86%	70%	91[illegible]	82%	118%	69%	117%	54%	131%	231%	120%	89%	97%	43,7%
Ch[illegible]a	10,2	100%	113%	102%	95[illegible]	91%	106%	102%	91%	87%	97%	94%	115%	101%	104%	7,8%
Gua[illegible]o	68,6	101%	116%	93%	125[illegible]	97%	104%	90%	96%	84%	79%	100%	109%	94%	112%	12,1%
[illegible]tá	78,1	90%	107%	95%	122[illegible]	97%	118%	95%	98%	75%	82%	127%	121%	80%	93%	16,0%
Mi[illegible] I	94,5			76%	83%	112%	105%	109%	122%	108%	111%	109%	85%	80%		15,0%
San Car[illegible]s	27,5	65%	65%	72%	91%	96%	108%	133%	108%	82%	95%	131%	107%	125%	124%	22,6%
Guat[illegible]é	36,3	82%	77%	90%	94%	91%	102%	111%	117%	101%	108%	132%	105%	100%	92%	13,7%
N[illegible]e	51,1	71%	70%	75%	97%	95%	100%	115%	144%	90%	117%	157%	99%	93%	77%	25,1%
A. San Loren[illegible]o	40,6	88%	70%	95%	90[illegible]	81%	94%	94%	135%	115%	118%	125%	106%	95%	94%	17,2%
Gran[illegible]e	32,7	88%	72%	81%	84[illegible]	81%	106%	119%	136%	96%	130%	146%	99%	82%	80%	22,8%
Guadalu[illegible]	22,1	103%	75%	100%	91[illegible]	88%	104%	126%	107%	94%	119%	112%	97%	92%	92%	12,7%
Cencepció[illegible]	6,8	91%	72%	86%	98[illegible]	93%	115%	120%	115%	92%	110%	131%	95%	90%	91%	15,5%
Tench[illegible]	4,5	106%	71%	95%	86[illegible]	87%	110%	120%	112%	87%	117%	127%	106%	88%	89%	15,6%
Desv. EEPPM (Nec,Paj,Dol)	8,0	137%	102%	113%	1[illegible]%	100%	104%	94%	85%	108%	101%	75%	98%	89%	89%	14,2%
Porce II	98,3		74%	89%	1[illegible]1%	93%	105%	115%	129%	95%	119%	118%	97%	85%	79%	16,0%
Porce III	[illegible]3,4											167%	94%	73%	67%	39,9%
Sinú Urrá	3[illegible],7		97%	106%	85%	100%	100%	116%	104%	101%	108%	104%	93%	102%	85%	8,3%
NATIONAL	1.55[illegible]8		88%	88[illegible]	92%	96%	106%	109%	117%	94%	99%	124%	99%	93%	96%	10,5%

*Own graph

Main conclusions

- **Accuracy** (magnitude) of Reanalysis (including MERRA) very much site-dependant. Good in flat terrains (coastal areas). In complex terrains (Andes) likely strong under- and overestimations (+-biases). Causes: surface smoothing and observational system. Consequently, AEPs in document likely to be strong underestimated
- Good ability of MERRA in capturing **time variations** in wind/solar resource (several R>+0,75 in case studies). Behaviour of several monthly wind/solar patterns found confirmed previous studies
- Apart from regional and local meteorological dynamics**, ITCZ main driver** of wind/solar but not for river in-flows intra-annual patterns. Colombia might have thinnest area within its extremes in the world. Statement requires detail investigation
- Although a wide variety of Rs and each generator should check tables separately:
  - **Intra-annual** complementarities (R> -0,5) mostly:
    - Hydro/wind and hydro/solar→North-North and South-South
  - **Inter-annual** complementarities (R> -0,5) mostly:
    - Hydro/wind→North in flows; winds Eastern Andes
    - Hydro/solar→North in-flows; insolations South and Eastern Andes
- **IAV** Solar resource < IAV wind resource < IAV hydro resource
- **Wind/solar power might back up Colombia** energy matrix in intra- and inter-annual times of low hydrology . Further multi-lateral* studies should be carried out (<u>validation of MERRA with IDEAM data</u>!, measurements campaigns, mesoscale simulations like WRF) as to confirm complementarities all over the country and implement schemes in the Colombian energy market, which recognize them and foester the development of these projects

*UPME, IDEAM, XM, generators, Banks and <u>Universities</u>

Thank you!

Questions?

Master Thesis: MERRA-based study of the wind/solar resources and their complementarity to the hydro resource for power generation in Colombia

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MERRA–based study of the wind/solar resources and their complementarity to the hydro resource for power generation in Colombia

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as a

Master Thesis

for the

Master of Science
Postgraduate Programme Renewable Energy
(PPRE)

Institute of Physics
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To Kerstin. Without you and your *thesis box*, it would not have been the same. Thank you for being always there, encouraging me, balancing life and making me to get the best of this stage of my life!

Declaration

I state and declare that this thesis was prepared by me and that no means or sources have been used, except those, which I cited and listed in the References section. The Master Thesis is in compliance with the rules of good practice in scientific research [1] of the University of Oldenburg Carl von Ossietzky.

Oldenburg, 1st of September 2015 __________________________________

Abstract

An energy generation matrix with large shares on hydro power such as the case of Colombia presents a strong vulnerability mainly caused by global meteorological. Principally driven by times of critical hydrology, an interest of investigating in detail the wind and the solar resources of the country has slowly started in recent years. Aiming to get a deeper knowledge about these resources as well as their complementarities for the Colombian hydrology, this self-started investigation was carried from February to August 2015.

Among other variables, hourly wind speeds @50m and surface solar irradiations of the MERRA Reanalysis for 1.014 grid points were processed for the period 2001-2014 and translated to monthly values. These grid points covered the whole Colombian territory. The sites with the highest resources in the country were selected: 13 wind sites and 14 solar sites. Because of the model resolution and local weather effects not "seen" by MERRA, the wind resource is likely to be strongly underestimated over the Andes (altitudes over 5.000m) but well reproduced in the coastal areas of the north. The solar resource seems to be slightly overestimated over the Andes. Although the Annual Energy Productions (AEP) of wind and solar parks were done, they are first estimates and are expected to be strongly underestimated, especially for the wind parks. In general, the found monthly patterns of the variables during the year are in accordance with the literature and are mainly explained by the Inter-Tropical Convergence Zone (ITCZ). Inter-Annual Variabilities (IAV) of 2,9-8,5% for the wind sites and of 2-2,6% for the solar sites were found.

The monthly in-flows of the rivers feeding 19 large hydro power plants representing 66,6% of the installed capacity in the country were processed for the same time span. The mean intra-annual Pearson´s correlation coefficients (R) for every year were found between all the pairs wind-hydro and solar hydro. With R>0,5, the intra-annual complementarities are mostly observed between in-flows of the north and winds of the north as well as in-flows of the south and winds of the south/centre. The same behaviour is seen for the hydro-solar pairs. Furthermore, the mean annual values of the resources were calculated and the inter-annual correlation coefficient for the same pairs were assessed. With R>0,5, the inter-annual complementarities are mostly observed between in-flows of the north and wind speeds of the Eastern Andes. For the hydro-solar, the largest coefficients are between in-flows of the north and solar insolations of the south/centre.

I wish you a pleasant reading through the document. Any comment will be very welcomed and can be addressed to the Email exhibited on the cover. Additionally, if used for future investigation, proper reference will be also appreciated.

Contents

List of main abbreviations and names

AEP: Annual Energy Production
CORPOEMA: Corporación para la Energía y el Medio Ambiente
COWI: Danish consultant company
CREG: Comisión de Regulación de Energía y Gas
ENSO: El Niño Southern Oscillation
EPM: Empresas Públicas de Medellín
GEOS-5: Goddard Earth Observing System Model, Version 5
GIS: Geographical Infortation System
GIZ: Deutsche Gesellschaft für Internationale Zusammenarbeit
GMT: Greenwich Mean Time
IAU: Incremental Analysis Update
IAV: Inter-Annual Variability
IDB: Inter-American Development Bank
IDEAM: Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia
IRENA: International Renewable Energy Agency
ISAGEN: Colombian utility
ITCZ: Inter-Tropical Convergence Zone
JMA: Japanese Meteorological Agency
MERRA: Modern Era Retrospective-Analysis for Research
MET mast: Meteorological mast
MDISC: Modelling and Assimilation Data and Information Services Center
NASA: National Aeronautics and Space Administration
NCAR: National Center for Atmospheric Research
NCEP: National Center for Environmental Prediction
NCSA: National Center for Supercomputing Applications
NOAA: National Oceanic and Atmospheric Administration
NOCT: Normal Operating Cell Temperature
Notus: German wind power developed
NP: Nominal Power
PPRE: Postgraduate Programme Renewable Energy
PR: Performance Ratio
PV: Photovoltaic
R: Pearson´s s product-moment correlation coefficient
R^2: Determination coefficient
SiGaia: Colombian company with experience in the systematization of geographic information
STC: Standard Test Conditions
UPME: Unidad de Planeación Minero Energética
XM: Compañía Expertos en Mercados

1 Introduction

Energy is a key matter for the development of any country. However, there are many factors which could heavily threaten its supply and thus, these have led governments to establish national policies in several countries for executing renewable energy projects, aiming to guarantee the energy security. In the case of Colombia, and taken into consideration that its national installed capacity strongly relies on hydro power plants (approx. 70%)[1] [3], there are three key issues which currently are playing a crucial role for the government to encourage the development of renewable energies:

- The weather variabilities might cause large scale droughts that affect directly the sensitive flows/levels of the Colombian hydro-power plants as observed in the national energy shortages and rationing programs in 1992 and 2003 or in the very high spot prices in 1998, which entailed a new regulatory framework for the development of a competitive market and system expansion –mainly thermal- with private participation in 1995[4][5]

- The execution of conventional power plants in Colombia, such as large hydro power plants, is getting critical due to environmental and social factors. As a result, some projects, such as the 400MW hydro power plant PORCE IV, have been indefinitely stopped because of it [6]

- The Colombian production of natural gas is foreseen to decrease in the coming years. In the *Natural Gas Balance in Colombia 2015*, a national deficit is foreseen in 2018 in a low scenario and in 2022 in a medium scenario by the UPME[2] (Colombia's national mining and energy planning unit from the Ministry of Energy)[7]. This is confirmed with the construction of the first Liquefied Natural Gas (LNG) import terminal in Colombia which started in July of this year, in the Caribbean coast [8]. Proposal for a second import terminal, this time in the Pacific coast, are in the agenda [9]

As a consequence, the Colombian Government and state/private companies have shown interest on renewables in the last years:

- Some utilities are carrying out several wind resource assessments, mainly in the Guajira (Colombia Caribbean coast), one of the windiest regions in Latin America. Nowadays, the Colombian utility EPM[3] is the unique with a wind park: *Jepirachi* [4], also located in the Guajira [10]

- The UPME has recognized for the first time on its *National Plan for the Expansion 2013-2027* that a likely complementarity between hydro and wind power in the north of Colombia

[1] Thermal power plants account for the remaining 30%. Gas power plants represent about 20% of the overall national system
[2] Unidad de Planeación Minero Energética
[3] Empresas Públicas de Medellín
[4] 15 x NORDEX N60/1,3MW turbines for a total rated capacity of 19,5MW. 60m diameter and 60m hub height. Installed in 2004[10]

might reduce the risks of supply for each individual source [11]. This might happen in the *dry months*[1], legally set by the CREG[2] (Regulatory Commission for Energy and Gas) [12]. Moreover, on its *National Plan for the Expansion 2014-2028,* the UPME presented studies for considering expansion scenarios with up to 474 MW of wind energy and 924,2 MW of a mix between solar-, biomass and geothermal power[13]

- The Law 1715 from 2014, intended to foster partnerships between the national government, the private sector and local authorities by facilitating the penetration of renewable energy and energy efficiency, was enacted in 2014. A clear decree must be ready in this year pointing out the framework and the granting incentives for the development of projects[14]

- Besides all this, the public tender 021-2014 "Methodology and pilot of complementarity and design of a national network for the measurement of the renewable energy resources in Colombia" was launched by the UPME in July 2014 and it was declared void. However, a new call of proposals was already launched this year for working with these topics [15]

Although there have been investigations about the complementarity of renewables in the country, they have purely focused on the wind resource in the Guajira region. Based on the latest and most relevant literature found, neither investigations about the complementarity of the wind resource in other regions nor investigations about the complementarity of the solar resource at all, related to the variety of the Colombian hydrology, have been carried out so far. As a consequence, and having in mind the information presented previously, it is clear the need for having a deeper understanding of the interactions between wind and solar resource patterns in areas in Colombia, which might provide an energy backup for the country in future times of low hydrology.

This study was born from a self-made proposal presented in 2014 after reviewing the information above. It is an academic project conducted as a Master Thesis for the Master of Science PPRE (Postgraduate Programme Renewable Energy) and was developed between February and August 2015 with supervision from the University of Oldenburg in Germany. Furthermore, an external supervision from the IDB (Inter-American Development Bank) was also provided.

The structure of the document is as follows: section 2 presents the scientific research question and the general objective of this study; section 3 provides state-of-the-art information about complementarity of renewables in Colombia along with a brief description of the Reanalysis data sets and the Pearson´s product-moment correlation coefficient; section 4 presents the methodology used in this study; section 5 exhibits the meteorological results: wind and solar resource of the country and the selected sites based on hourly Reanalysis data from the last 14

[1] These months (December to April) are months considered as months with a low national hydrology
[2] Comisión de Regulación de Energía y Gas

years; besides this section 5 also presents the meteorological results of the rivers of the selected hydro power plants in Colombia based on local river in-flows; section 6 gives first estimates of energy generation from the selected sites and hydro power plants; section 7 discusses and compares the obtained results; section 8 draws the main conclusions of the study; section 9 proposes future works to be executed; section 10 lists the references used for this study and section 11 shows appendices considered important for a detailed understanding of this study.

2 Research question and general objective

Research question: For power production in Colombia, how complementary are the intra-annual[1] distributions of the wind and solar resources of the country to the hydro resources found in sites where the current hydro power plants are located?

General objective: The main objective is to analyse how complementary the patterns of the wind and the solar resources in Colombia are related to the hydro resources currently used for energy generation during the year. The analyses are based on meteorological Reanalysis data and river in-flows data. Even though the unit of analysis is set as selected grid points distributed all over the country, the study offers general recommendations to transmission systems operators, electricity market participants, government authorities and policy makers of Colombia on where to develop further investigations as to recognize the advantages of the complementarity of future wind and solar power systems for the hydro power generation park. Furthermore, the first Reanalysis-based annual wind and solar resource indexes for the selected sites in Colombia are presented in order to improve correlations for long-term energy yield assessments and thus, to improve the financing opportunities of future projects based on wind and solar energy in Colombia

For the purposes of this study, neither technical characteristics of the transmission grid in the country nor the economy of renewable power systems will be addressed. Market-related operational strategies of the hydro power plants are also not considered.

Note: It is very important to remark that the add-on of this study resides in the monthly and annual behaviour of the wind, solar and hydro resources as to analyse the contribution of the wind/solar resource to the hydraulic generation matrix in Colombia, and not in accurate values of energy production, which should be addressed carefully and should not be used for commercial purposes without the corresponding future works mentioned later on.

[1] During the year

3 Background

3.1 State of the art of the complementarity between renewables in Colombia

In the last years, some studies have been carried out related to the relationships between the renewable energies in Colombia and its generation matrix. These have focused all the efforts in analysing the wind resource the region of the Guajira, north of the country, along with the hydro regime in the country. This, because several information sources assign this site with the best wind resource. Regarding the solar resource, only one study was found with a minor contribution to the topic and, in general, no evidence of the complementarity of the solar resource in Colombia was found. Following, a brief description of the latest and most relevant scientific literature found about the subject is presented chronologically:

Although more targeted to the economy of energy markets as to the complementarity itself, Franco and Dyner, from the National University of Colombia (Medellín) modelled a portfolio of wind, hydraulic and thermal generation with data[1] from EPM in 2004 [16]. They determined that energy purchases in the spot market would considerable decrease for EPM especially on El Niño occurrences due to high wind energy production in the Guajira in periods with low hydroelectric generation. Furthermore, they concluded that although the profitability of the modelled portfolio decreases, so does its risk.

The first work about the complementarity itself is found in The World Bank study conducted by Vergara et al. in 2010 [4]. Among many other analyses, a complementarity examination was carried out. Hourly production data from XM [2] (Power system operator and market administrator in Colombia) between 2004 and 2009 for the wind park Jepirachi, was combined with hourly wind data from a meteorological station[3] nearby (Puerto Bolivar, @10m, 1986 - 2008) as to perform a regression for the energy generation of the wind park. Mean monthly wind speeds were calculated and plotted together with mean monthly discharges[4] of four rivers[5], located in different regions of the country and with different intra-annual patterns. A brief description of when high wind speeds and low in-flows happened was done for each of the four cases.

In 2010, the Colombian consultant company CORPOEMA[6] (Corporation for the energy and environment) develops an extensive study with three reports. In its third report [17], both the complementarity of the wind and the solar resources are shortly exhibited . On the wind side, and based on a graph shown by EPM (where the monthly wind energy of the wind park

[1] Not specified in detail
[2] Compañía Expertos en Mercados
[3] From IDEAM. 83% of wind data available
[4] In this study, understood as in-flows. The information source is not clear: “databases for simulation of the interconnected hydrothermal power system”
[5] Nare, Guavio, Salvajina Cauca and Magdalena Betania. Starting data from 1946-1979, depending on the available information for each river, until 2009. All these rivers are considered in this study
[6] Corporación para la Energía y el Medio Ambiente

Jepirachi is presented along with the monthly availability of hydro resource in the Magdalena-Cauca basin), the study mentions how the wind speeds in the Guajira are larger from January to April, part of the established CREG *dry months*. Based on data from XM, it also indicates how the peak of the power produced by the wind park (at 3pm) is between the secondary peak (at 11am) and the principal peak (at 7pm) of the daily national power demand. Furthermore, El Niño occurrences are also commented. On the solar side, the CORPOEMA study states that no information about the inter-annual solar resource is available for Colombia. However, based on two maps[1] of the daily solar insolation (one for the annual mean and one for mean in January), the study points out how increments of the solar resource in some areas in January – part of the CREG *dry months*- could contribute to the energy generation matrix. Besides this, it is also mentioned how solar energy could assist to the secondary peak of the daily national power demand, due to the natural sinusoidal behaviour the solar energy, but not to the principal peak.

In 2011 Ealo Otero[2] released his Master thesis for the National University Colombia (Medellín) [5]. Among many other interesting analysis and findings, a detailed complementarity study was properly carried out here for the first time. Here the executed steps of interest of this study:

- Mean monthly wind speeds of the previously mentioned meteorological station Puerto Bolivar (hourly data @10m, 1986-2006) were calculated[3]. The mean monthly in-flows[4] of 14 rivers (monthly data; starting date from 1959-1970 until 2001-2005 [5]) were also calculated, representing a comprehensive overview of the monthly hydro regime of the country. Afterwards, the Pearson´s correlation coefficient between the monthly information of Puerto Bolivar and each of the rivers were assessed

- Wind data from the Reanalysis NCEP/NCAR for a point in the Guajira was retrieved (monthly data, @10m, 1948-2009) and the monthly Pearson´s correlations coefficient, R, between it and the Puerto Bolivar was assessed as 0,66

- Similarly as the first bullet point, the Pearson´s correlation coefficients between the mean monthly river in-flows of 6 rivers flowing through 5 hydro power plants[6] and 1 project[7] of ISAGEN and the mean monthly wind speeds at Puerto Bolivar were found. The same procedure was done with the values of the NCEP/NCAR Reanalysis point. The correlation coefficients were compared.

[1] The source of the maps is not clear
[2] Who kindly contributed with comments and answers to this study through a general review done by ISAGEN
[3] 79% of wind data available
[4] Unknown source of information
[5] depending on the available information for each river
[6] San Carlos, Jaguas, Miel I, Calderas and Amoyá. All considered in this study
[7] Sogamoso. Not considered in this study

- Calculations of the wind energy generation of a simulated wind park of 20MW was executed based on hourly data from the MET mast Parque Eólico (10min @20, 40 and 60m, 2008-2010, owned by ISAGEN) regressed with the Puerto Bolivar information and the Reanalysis point. The monthly generation curve of the wind park was calculated with the power curve of the same wind turbines in Jepirachi and the result was compared together with the reported monthly generation of Jepirachi. Although the behaviour of the curves are quite similar, the magnitudes of the assessment (81,9GWh/year) overestimated the reported generation of Jepirachi (52,6GWh/year).

In 2012, Robinson et al., at The Oxford Institute for Energy Studies, published a paper [18] where the correlation between wind speeds in the Puerto Bolivar station and the sea surface temperature anomaly (El Niño[1]) was analysed getting a monthly correlation coefficient[2] of 0,274. Also interesting is the OLS[3] regression they did between wind speeds at Puerto Bolivar (@10m, w_{10}) and calculated[4] wind speeds from Jepirachi (@60m, w_{60}) between 2004 and 2011 finding the equation $w_{60} = 3{,}20 + 0{,}84w_{10}$ with a monthly[5] R^2, coefficient of determination, of 0,58.

During the development of this study, the UPME officially published its *Reference expansion plan for generation and transmission until 2014-2028* [13]. There, the wind energy in the Guajira is widely exhibited to the public in Colombia. Hourly wind speeds from a MET mast located in the Guajira (@80m, from 2012 to 2014; owned by the project developer Jemeiwaa Ka'i) were compared to wind data of a point of the Reanalysis MERRA in the Guajira[6]. Hourly and daily correlation coefficients of over 0,70 were found[7]. Furthermore, the wind speeds of the MET mast were extended using the MERRA point from 1994 to 2014 and extrapolated to 90m and 120m with a Hellman coefficient[8] (α) of 0,25. Based on them, on an air density of 1,15kg/m^3 and with 15% of losses, the energy production of 474MW of wind power is calculated and plotted against the calculated national hydroelectric generation from 2018 to 2028 as to show the complementarity in the CREG *dry months*.

Also while developing this study, a work with four reports developed by COWI was released. The second [19] and the third [12] reports are of interest here because these analyse a fictive 400MW wind park in the Guajira:

---

1 It seems to be on a monthly basis
2 Not detailed if it is the correlation one, R, or the determination one, R^2↕
3 Ordinary Least Squares
4 Done by taking the generation of the wind park with the power curve of the turbines there (N60)
5 It seems to be on a monthly basis
6 Likely the same point and variable (wind speeds @50m) used in this study called "wind site Guajira" and explained later on
7 Not specified if the coefficient is R or R^2
8 Used by the empirical power law to calculate the wind speed w from the height $z1$ to the height $z1$ [100] $w_{z2} = w_{z1}\left(\frac{h_2}{h_1}\right)^{\alpha}$

- On the second report, the mean wind speed of a meteorological station[1] (hourly, @10, 2001-2009, w_{10}) in the Guajira was calculated as 6,1m/s. The mean wind speed of a MET mast[2] nearby (hourly, @50m, 2007-2013, w_{50}) was calculated as 7,5m/s. The equation between them is found as $w_{10} = 0{,}0326 + 0{,}7423w_{50}$ with a weekly R^2, coefficient of determination[3], is 0,95. With these two information sources, a 12 years @50m data set was combined with the process MCP[4]. Furthermore, data from a point of MERRA[5] from 1983-2012 was retrieved and a R^2 of 0,85 was found between monthly data of the 50m MET mast and the MERRA point. Consequently, a long term mean wind speed of 8,2m/s @50m was stated. For the 12 years, corrected with the MERRA, an annual standard deviation of 12,5% was calculated. Besides this, a long term trend for the MERRA data for this point is shown with the equation $y = -0{,}0321x + 72{,}735$ and thus, a de-trending[6] was applied to the data

- On the third report, the complementarity was analysed. Monthly in-flows from 26 rivers[7] were made available by the UPME (1997-2013). These were aggregated in a called overall national hydro pool and a mean monthly curve was obtained. Moreover, production data of four[8] hydro power plants were made also available by the UPME (1995-2013). These were compared with their river in-flows and no clear relation between them was found. This was explained with the presence of dams. With this information, two analyses were executed: a comparison between wind speed and river in-flows; and between wind energy and hydroelectric energy. For the first one, the wind speed in the Guajira was compared with the overall national hydro pool and a correlation coefficient R of -0,18 was found. Correlation coefficients for the in-flows of the four hydro power plants were also calculated. Furthermore the months where the wind speed was higher than its average and where the in-flow of the hydro pool was lower than its average were checked. This happens mostly from January to March[9], also possible in April and to a less extent in December. A relation between the CREG *dry months* and over-average wind speeds was confirmed. However, for the second analysis (wind energy – hydro energy), this could not be confirmed[10].

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[1] Name not given. In this study marked as "Meteo station X 10m"
[2] Name not gives. In this study marked ad "MET mast X 50m"
[3] Although there named correlation coefficient
[4] Measure Correlate Predict
[5] Likely the same point and variable (@50m) used in this study called "wind site Guajira" and explained later on
[6] Critical point because no scientific arguments are presented for the procedure
[7] Likely the same rivers and in-flows used in this study
[8] Salvajina, Betania, Guatapé and Guavio. All considered also in this study
[9] But not all the years
[10] Expected as there was no correlation between the in-flows and the production data. Contrary to this study where: the in-flows will be taken for the complementarity analysis. The production of the hydro power plants was also assessed with the in-flows. No direct production data was taken. This is explained later on in the section Methodology

3.2 Reanalysis datasets

This is study is mainly based in Reanalysis data. Therefore, it is important to give an overview about what it is. Reanalysis is a systematic approach for developing a comprehensive data set for climate monitoring and research. It can be either atmospheric, oceanic or coupled. Within it, a data assimilation scheme together with a numerical model of the atmosphere (both “frozen” in time) ingest weather observations from a quality-assured monitoring network worldwide every 6 to 12 hours. This provides a dynamically consistent estimate of the climate state at each time step, aiming to get a homogeneous data set with high temporal and spatial resolution. The generated data set provides three-dimensional global fields, from the Earth’s surface to well above the stratosphere of a wide quantity of parameters [20] [21].

A Reanalysis typically extends over several decades and, currently several million of observations from around the globe are ingested at each time step. The observations are coming from a broad network of measurements distributed in different places. They include but are not limited to data from surface measurements, ships, pibal – piloted balloons, radiosondes, buoys, aircrafts, geostationary satellites, argo floats and polar-orbiting satellites, among others [22].

Produced data sets from the Reanalyses are used extensively in climate research for monitoring and comparing current conditions with those of the past (see example on Figure 1) and for preparing climate predictions. Furthermore, information derived from Reanalyses is also being used in commercial and business applications in sectors such as energy, agriculture and water resources.

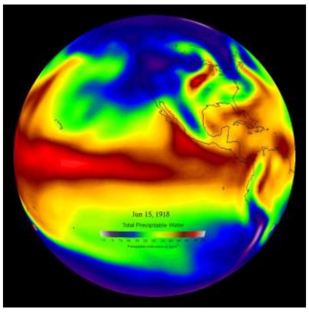

Figure 1: Simulation from a Reanalysis. Precipitable water, El Niño June 15th 1918. Taken from [23]

As a scientific model, Reanalysis systems have strengths and limitations [24]. On one side, within the key strengths, it can be summarized that Reanalyses:

- Provide three-dimensional global data sets with consistent spatial and temporal resolution over 3 or more decades with hundreds of variables available
- Incorporate millions of observations into a stable data assimilation system that would be nearly impossible for an individual to collect and analyse separately, enabling a number of climate processes to be studied

- Are relatively straightforward to handle from a processing standpoint (although file sizes can be very large)

On the other side, between the most important key limitations, it can be found that:

- There are observational constraints, and therefore reanalysis reliability, can considerably vary depending on the location, time period, and variable considered
- The changing mix of observations, and biases in observations and models, can introduce spurious variability and trends into reanalysis output

3.3 Pearson´s product-moment correlation coefficient

The term "complementarity" in this study refers directly to the Pearson product-moment correlation coefficient (PPMC; denoted with the letter R in the literature; hereafter called correlation coefficient) [25][26]. This coefficient measures the strength and direction of linear relationships between *two variables* and is calculated as the Equation 1shows:

$$\boldsymbol{Pearson´s\ coefficient:\ R_{xy} = \frac{cov(x,y)}{\sigma_x \sigma_y}}$$

$$Covariance:\ cov(x,y) = \frac{1}{N}\sum (x_i - \bar{x})(y_i - \bar{y})$$

$$Standard\ deviation:\ \sigma_x = \sqrt{var(x)} = \sqrt{\frac{1}{N}\sum (x_i - \bar{x})^2} \qquad Variance:\ var(x) = \frac{1}{N}\sum (x_i - \bar{x})^2$$

$$Mean:\ \bar{x} = \frac{1}{N}\sum x_i$$

Equation 1: Pearson´s coefficient (Top) between two variables (x, y) with N observations

Pearson´s correlation coefficient is independent of the scale of the magnitudes of the variables[5]. It ranges from -1 to 1. The sign of the coefficient indicates the direction of the relationship while the magnitude indicates its strength. A value of 0 indicates that there is no association between the two variables: their behaviours are totally independent. A positive value indicates a positive, or direct, association: as the value of one variable increases, so does the value of other. A negative value indicates a negative, or inverse, association: as the value of one variable increases, the value of other decreases.

As to better understand it, an example is exhibited. The time-plots and the scatterplots of three different correlation behaviours between two variables are shown in the Figure 2:

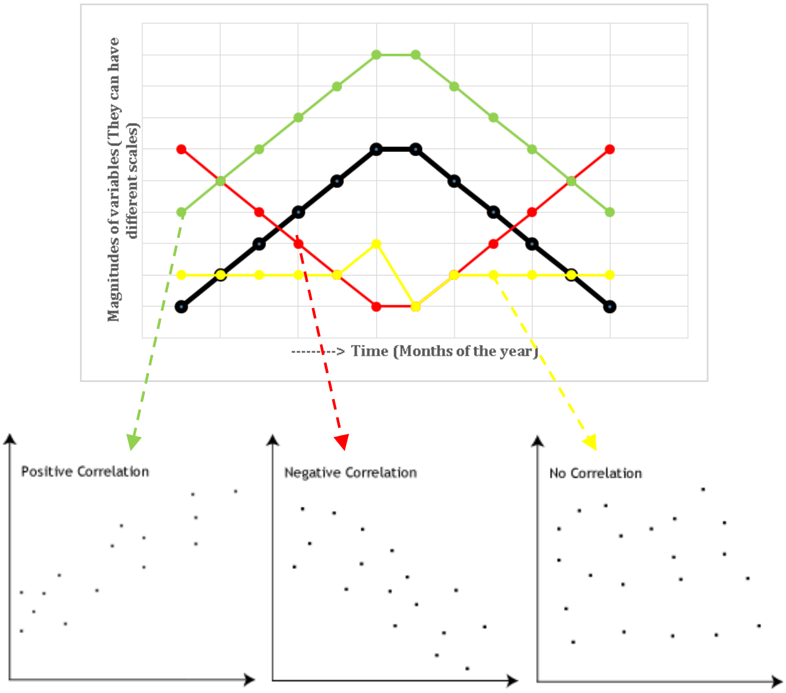

Figure 2: (Top) Example of time-plot of the variable base (black) and variable to study with positive correlation (green), negative correlation (red) and no correlation (yellow) through time. (Bottom) Scatterplots of positive, negative and no correlations. The values of the base variable are on the x-axis; the values of the variable to study are on the y-axis. Self-drawn and taken from [27]

It can be observed that the green line in the figure before is perfectly following the behaviour of the base line, the black one. This, independently of the scale of the magnitudes between these variables. As a consequence, it would get a correlation coefficient of +1, a perfect positive correlation. The red line, on the contrary, has a perfect inverse behaviour as the base line. Thus, this line would get a correlation coefficient of -1, a perfect negative correlation. The yellow line has no relation with the behaviour through the time of the black line. It means that both variables are totally independent and the correlation coefficient between them would be 0, no correlation.

In this study, **the higher the magnitude of a negative Pearson´s correlation coefficient** (the red line compared to black line in the example), **the more complementary two variables are**. The magnitude of the complementarity will be qualified as shown in Table 1:

	Coefficient, r	
Strength of Association	Positive	Negative
Small	.1 to .3	-0.1 to -0.3
Medium	.3 to .5	-0.3 to -0.5
Large	.5 to 1.0	-0.5 to -1.0

Table 1: Guidelines adopted for interpreting the Pearson´s correlation coefficient, R. taken from [27]

4 Methodology

4.1 Selection of a global atmosphere Reanalysis

Reanalysis data sets are available for either regional or world-wide scale. On the global scale, an extensive scientific process has been executed the last in order to improve the quality of the data sets. As a result, three generations have evolved through the time [28]: *First generation*: NCEP/NCAR R-1, ERA-15; *Second generation*: ERA-40, NCEP/DOE R-2, JRA-25 and *Third generation*: JRA-55, CFSR, ERA-Interim, MERRA. Besides these, scientific centres are working on future models such as NOAA 20CR, ERA-CLIM2 and ERA-20C.

For the scope of this study, the analysis was focused on the four current state-of-the-art datasets (*Third generation*). An overview of the four data sets can be found on the Appendix 11.1 [20][21][24]. From the four options, the American CFSR (Climate Forecast System Reanalysis) has been the first atmosphere-ocean coupled system. This brings along a further step compared to the other three, where computations are done for the atmosphere but not for the oceans. This is a very valuable tool for future scientific investigations. However, relatively few evaluations of the CFSR have been conducted making its performance still not well-known [24]. Regarding the Japanese JRA-55, although it has a longer time span (from 1958), it has a native spatial resolution of 1,25° (approx. 140km at the equator). This is not as detailed at the ones of the ERA-Interim and the MERRA. In the case of the ERA-Interim, this data set has a coarser native spatial resolution than the MERRA and, moreover, the lowest time resolution provided is a 3 hours [29], not as the hourly values from the MERRA. As a result, the MERRA Reanalysis dataset is chosen for the analysis of this study. A detailed description of the system is presented next.

4.2 Revision of the MERRA Reanalysis

The Modern-Era Retrospective analysis for Research and Applications (MERRA) is a state-of-the-art atmospheric Reanalysis undertaken by NASA´s Global Modelling and Assimilation Office with two primary objectives: to place observations from NASA´s Earth Observing System (EOS) satellites in a climate context and to improve upon the hydrologic cycle represented in earlier generations of Reanalyses. It uses the Goddard Earth Observing System Model version 5 (GEOS-5), which is a circulation model based on finite-volume dynamics found effective for transport processes in the stratosphere. The GEOS-5 works with an Incremental Analysis Update (IAU) procedure in which the analysis correction is applied to the forecast model gradually, through an additional tendency term in the model equations during the corrector segment. MERRA uses a three-dimensional variational (3D-Var) analysis algorithm based on the Grid-point Statistical Interpolation scheme (GSI) with a six-hour update cycle [30].

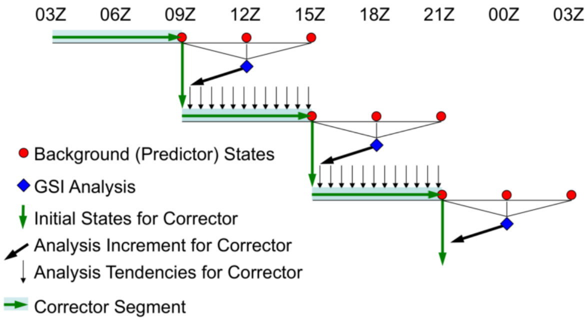

Figure 3: Schematic of the IAU implementation in GEOS-5 [31]

MERRA receives about 3,5 million of observational inputs from all around the world every 6 hours. However the actually assimilated observations are about 1,5 million [32] due data thinning and data quality filtering, used to reduce computational burdens. There are 6-hourly instantaneous collections of data at synoptic times (00, 06, 12, 18 GTM). Time-averaged collections contain either hourly, three-hourly, monthly or seasonal means. Theses time-averaged collections consist of a continuous sequence of data averaged over the indicated interval and time stamped with the central time of the interval. For hourly data, these times are 00:30, 01:30, 02:30 GTM, etc. Surface data, near-to-surface meteorology and vertically integrated fluxes and budgets are produced at one-hour intervals [33]. The time span goes from 1979 to the present for near-real-time climate analyses. However, data is separated in three Streams as shown in the Figure 4:

Stream	Dates[1]	Number of years
1	1979 -1992	14
2	1993 – 2000	8
3	2001 - 2014[2]	14

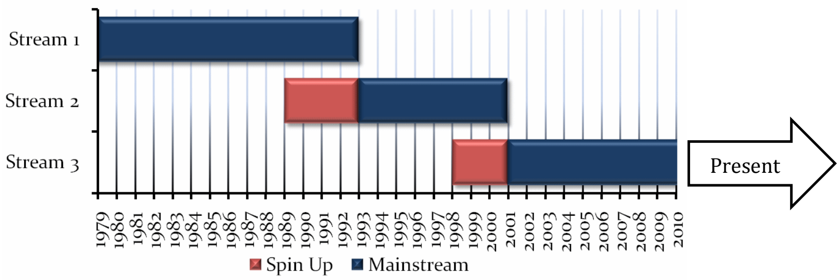

Figure 4: MERRA streams. Taken from [34]

The vertical resolution corresponds to 72 model levels and 42 pressure levels from the surface to the top level at 0,01 hPa (approx. located at an altitude of 80 km up in the atmosphere). Horizontally, MERRA has the following native spatial resolution:

	Grid points available for the globe	First point	Step[3]	Last point
Longitude	540	180° West	2/3° ≈ 0,66° ≈ 74,2 km at the equator	179,33° East
Latitude	361	90° South	1/2° = 0,5° ≈ 55,3 km at the equator	90° North

Table 2: Horizontal structure available of MERRA data

[1] Starting on the 1st of January at 00:30 GTM and finishing the 31st of December at 23:30 GTM
[2] MERRA Reanalysis keeps running in the present
[3] Considering that 1° of longitude represents approx. 111,321 km and 1° of latitude represents approx. 110,567km at the equator [101]

As displayed in Figure 5, the point with the red arrows on the bottom-left corner signalizes the geographical starting point of the data. For the longitudes, values increase to the right (East). For the latitudes, values increase to the top (North). Furthermore, the symbols used for each hemisphere are presented in the Table 3:

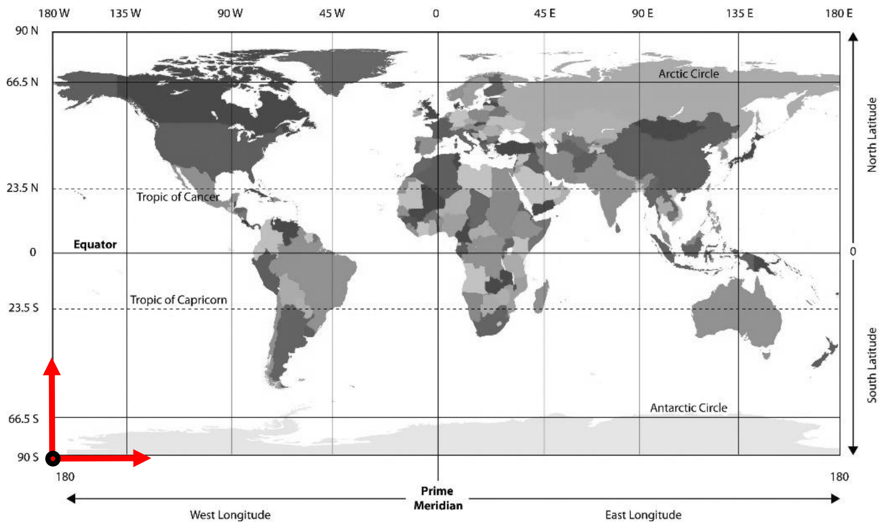

Figure 5: World map with longitudes and latitudes. When reading data from MERRA, to the East, longitude-locations increase, to the North, latitude-locations. Taken from [35]

	Hemisphere	Symbol	Range
Longitude	West	(-)	From -180 (or 180W) to +179,3 (or 179,3E)
	East	(+)	
Latitude	South	(-)	From -90 (or 90S) to +90 (or 90N)
	North	(+)	

Table 3: Symbol of each hemisphere on the MERRA data[1]

Each of the MERRA grid points is representative for an area covering approx. 4.107[2] km^2 (55,3km in the latitude times 74,2km in the longitude). The grid point is located in the center of this area [36].

4.3 Data processing

In order to select the most appropriate Reanalysis data for this study, the following area coverage was set for this study:

[1] As an example, a longitude of -82,66° refers to 82,66°West and a latitude of -5,5° refers to 5,5°South
[2] 55,3 km x 74,2 km ≈ 4.103 km^2

	Number of grid points used	First point	Last point	Distance between first and last point
Longitude	26	- 82,66°	- 66°	~ 1.855 km
Latitude	39	- 5,5°	+ 13,5°	~ 2.101 km

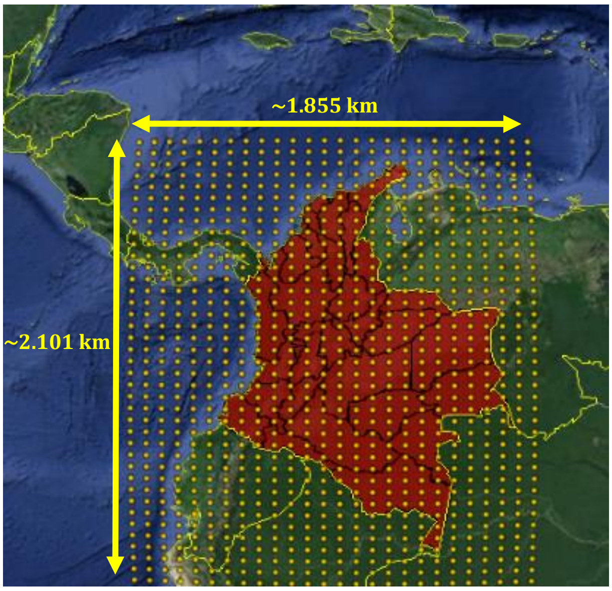

Figure 6: 1.014 grid points (yellow dots) of MERRA used in this study fully covering the Colombian territory (in red) [37]. Projected in © Google Earth

1.014[1] grid points were retrieved and include information also for the insular territory (San Andrés and Providencia Islands on the Caribbean Sea). Besides this, more territory as needed was covered in order to prepare the data for future works. After an extensive analysis of the wide variety of provided parameters from MERRA [38] [33], *ten variables* were chosen to understand the meteorological (wind, solar and hydro) resource of Colombia and to calculated estimates of energy generation based on them:

Name	Description	Collection	Frequency [h]	Horizontal resolution	Vertical levels	Unit
U50M	Eastward wind @ 50m above surface	tavg1_2d_slv_Nx, MERRA IAU 2d atmospheric single-level diagnostics	1, time-averaged	Native	1	[m/s]
V50M	Northward wind @ 50m above surface	tavg1_2d_slv_Nx, MERRA IAU 2d atmospheric single-level diagnostics	1, time-averaged	Native	1	[m/s]
Z0M	Roughness length, momentum	tavg1_2d_flx_Nx, MERRA IAU 2d surface turbulent flux diagnostics	1, time-averaged	Native	1	[m]
RHOA	Surface air density	tavg1_2d_flx_Nx, MERRA IAU 2d surface turbulent flux diagnostics	1, time-averaged	Native	1	[kg/m^3]
DISPH	Displacement height	tavg1_2d_slv_Nx, MERRA IAU 2d atmospheric single-level diagnostics	1, time-averaged	Native	1	[m]

Table 4: Variables to be retrieved for analysing the wind resource

[1] 26 longitudes x 39 latitudes = 1014 grid points

Name	Description	Collection	Frequency [h]	Horizontal resolution	Vertical levels	Unit
SWGDN[1]	Surface incident shortwave flux	tavg1_2d_rad_Nx, MERRA IAU 2d surface and TOA radiation fluxes	1, time-averaged	Native	1	[W/m^2]
T2M	Temperature at 2m above the displacement height	tavg1_2d_slv_Nx, MERRA IAU 2d atmospheric single-level diagnostics	1, time-averaged	Native	1	[K]

Table 5: Variables to be retrieved for analysing the solar resource

Name	Description	Collection	Frequency [h]	Horizontal resolution	Vertical levels	Unit
RUNOFF	Overland runoff	tavg1_2d_lnd_Nx, MERRA IAU 2d land surface diagnostics	1, time-averaged	Native	1	[kg/m^{2}s]
PRECTOT	Total surface precipitation	tavg1_2d_lnd_Nx, MERRA IAU 2d land surface diagnostics	1, time-averaged	Native	1	[kg/m^{2}s]

Table 6: Variables to be retrieved for analysing the hydro resource

Name	Description	Collection	Frequency [h]	Horizontal resolution	Vertical levels	Unit
PHIS	Surface geopotential	const_2d_asm_Nx, MERRA DAS 2d constants	Constant	Native	1	[m^2/s^2]

Table 7: Variables to be retrieved for analysing the MERRA system itself

There are nine chosen variables which have an **hourly temporal resolution** and one constant variable, PHIS. The quantity of data is a very delicate issue in this study. Just to give a general overview of the quantity of data, for the 1.014 grid points selected there would be:

Stream	Number of years	Number of days	Number of hours	Quantity of data[2]
Constant variable (PHIS)				1014
1	14	5.114		1.119.212.640
2	8	2.922		639.550.080
3	14	5.113	122.712	1.119.212.640
Total of data for all streams				2.877.976.374

Table 8: Data to retrieve and process per Stream for the 1.014 grid points selected

2,8 billion of data generate a sizeable data set . Although many other interesting variables in the MERRA dataset and more data (Stream 1 and 2, with data from 1979) were intended to be used in this study at the beginning, they have not been included due to time- and computational-constraints. As a result, only the Stream 3 of MERRA, 14 years from 2001 to 2014, are included in this study.

[1] Definition: "Incident solar radiation (0,175 to 3,85 µ) at the surface for all-sky conditions. Since we do a single atmospheric radiative transfer calculation in a grid box, we assume the incident radiation is the same for all surface tiles within the box. GEOS-5.6.2 uses a solar constant of 1365 W/m^2" [38]. The spectral response of today´s PV technologies are within the range of wavelengths given by the variable SWGDN. Please refer to Figure 104 in the Appendix 11.16

[2] $data_i = v_t \times \sim 8.760 \left[\frac{h}{year}\right] \times y_{s_i} \times [grid\_points]$; Nine time-dependent variables, v_t, y_{s_i} refers to the years of each MERRA stream *i*.

MERRA Data holdings can be accessed and downloaded as *Products* or as *Data Subsets* on different ways [39]. Since the *Products* provide data for the whole globe (540 x 361 grid points), they contain too much information for the purpose of this study. Therefore, the *Data Subsets* were selected for this study. In the MDISC Data Subset webpage [40], these can be delimited to a specific geographical area, to a temporal time span and to the *ten* variables of interest for this study. Due to the size of the data-package to work with, the available worldwide references of MERRA-related and HDF-related (Hierarchical Data Format) projects as well as due its high programming performance, the software © Matlab [41] has been used. A student version of the software (R2013a) was provided by the University of Oldenburg, for the purpose of this Master Thesis.

GEOS-5 files, the base for the MERRA data set, are organized on the HDF-EOS format, which is an extension of the HDF, developed at the NCSA (National Center for Supercomputing Applications)[33, Sec. 2]. The HDF is designed to store and organize large amounts of scientific numerical data across diverse operating systems and machines and support a wide variety of data types: data arrays, tables, text, raster images and their colour palettes [42][43]. Each daily file from the MERRA *Data Subsets* contains information about longitudes, latitudes, the time and the values of the variable(s). The longitudes and latitudes are given with the symbols of Table 3 and represent the selected geographical area. The time vector contains the number of hours of the day, but not the absolute time. In order to have absolute times, an hourly time vector for the whole Stream 3 was created. It is important to note that the files refers to the time at GMT (Greenwich Mean Time). As Colombia is situated at -5GMT, all values extracted from MERRA were delayed 5 hours to get the real Colombian time.

	GMT	Colombia, -5GMT
First data	00:30 1st of January of 2001	19:30 31st of December 2000
Last data	23:00 31st of December of 2014	18:30 31st of December 2014

Table 9: Original times in MERRA *Data Subsets* (GMT) and real time for Colombia (-5 GMT) for the Stream 3

For each variable, the values of every single hour are presented in a matrix with the size of the number of longitudes times the number of latitudes. Hourly 26 x 39 matrices were obtained. All the matrices were stacked up relating them with its respective Colombian time stamp. As a result, the 3-dimensional matrices allowed to get data moving either through time or through space for the analysis of this study.

4.4 Selection of wind and solar sites to analyse

Four criteria were applied for selecting the wind and the solar sites to analyse. On one side, the highest meteorological resources in the country (either wind speed or solar insolation) were selected. On the other side, three real-life criteria were used as to restrict the likely places where projects might be implemented. This will be explained right afterwards.

Highest magnitudes of mean wind speed @ 50m: Considering the variables U50M and V50M, the hourly Eastward and Northward wind @50m above surface, Equation 2 shows the calculation of the mean wind speed @ 50 for each point:

$$\overline{WS}_{\ Stream3,i,j}\left[\frac{m}{s}\right] = \frac{1}{Hours\ Stream3} \times \sum_{hour=1}^{Hours\ Stream3} WS_{hourly\ i,j}$$
$$\therefore hourly\ wind\ speed\ \left[\frac{m}{s}\right] : WS_{hourly\ i,j} = \sqrt{U50M_{i,j}{}^2 + V50M_{i,j}{}^2}$$

Equation 2: Magnitude of the mean wind speed @ 50m in Stream 3 for the grid point with longitude "i" and latitude "j"

As a result, a map with the mean wind speed @ 50m for every grid point was plotted. Additionally, for visual purposes, an *interpolated shading*[1] was executed in © Matlab and the mean values of U50M and V50M were separately computed for the 14 years as to generate wind speed vectors. This was superimposed as image overlay in © Google Earth.

Highest mean annual surface solar insolation: A similar process was carried out for the solar resource. However, the annual surface solar insolation was calculated as:

$$\overline{SI}_{annual\ \ i,j}\left[\frac{kWh}{m^2\ year}\right] = \frac{1}{Years\ Stream_3} \times \sum_{hour=1}^{Hours\ Stream_3} SWGDN_{i,j} \times \frac{1}{1000}$$

Equation 3: Mean annual surface solar insolation for the grid point with longitude "i" and latitude "j" in Stream 3

Consequently, a map with the mean annual surface solar insolation for every grid point was plotted. For visual purposes, the same interpolation in © Matlab was carried out and the image was overlaid in © Google Earth.

Real-life criteria: As to restrict this study to the most real-life conditions over the Colombian territory, the following criteria were consequently applied:

- The coverage of the national transmission grid and its future expansion[2]: expected grid in 2028 taken from the UPME [13]
- The location of the national natural parks[3]: taken from the institution Natural national parks of Colombia [44]
- The grid of main roads within the country[4]: observed directly from the layer *Roads* in © Google Earth

All the maps were geo-referenced and superimposed in © Google Earth. As a result 13 wind sites and 14 solar sites were selected as potential areas of future development.

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1 Linear interpolation between the four corners of the MERRA box
2 Please refer to the Appendix 11.10
3 Please refer to the Appendix 11.11
4 Please refer to the Appendix 11.12

Furthermore, as to find the Pearson´s correlation coefficient for the meteorological results, the monthly values for the 168 months of the 14 years[1] were also calculated for the wind and the solar resource:

$$\overline{WS}_{monthly\ i,j}\left[\frac{m}{s}\right] = \frac{1}{Hours\ month} \times \sum_{hour=1}^{Hours\ month} WS_{hourly\ i,j}$$

Equation 4: Mean monthly wind speed @ 50m for the wind site with longitude "i" and latitude "j"

$$\overline{SI}_{monthly\ i,j}\left[\frac{kWh}{m^2\ month}\right] = \sum_{hour=1}^{Hours\ month} SWGDN_{i,j}$$

Equation 5: Mean monthly surface solar insolation for the solar site with longitude "i" and latitude "j"

A normalization of this monthly information was also executed as to focus on the intra-annual[2] behaviour of the resource and not on the magnitude of it. This normalization was done with the average of its year. For example, the normalized values for January 2001 were done the average value of the year 2001.

$$x_{Normalized\ m,y}[\%] = \frac{x_m}{\overline{x_y}} \times 100$$

Equation 6: Normalized-with-the-average monthly value of a variable "x" on the month "m" of the year "y"

4.5 Hydro power plants in Colombia and their rivers

Hydrological variables from MERRA (RUNOFF, overland runoff and PRECTOT, Total surface precipitation) were also retrieved for the Stream 3. The mean values were plotted with the original resolution of MERRA. The results are shown in the Appendix 11.2. However, together with time constrains, this data could not be included in this study because it was preferred to work with local data from Colombia about the hydro power plants made available by the power system operator and market administrator in Colombia, XM [3][45] . As shown in Table 10, large[3] power plants are centrally dispatched by XM. Smaller power plants are not centrally dispatched and thus, are independently operated. Furthermore, it can be observed that large hydro power plants represent approx. 66,6% of the total installed capacity of the country compared with the 3,8% of the small hydro power plants. As a result, this study focuses on the behaviour of the rivers flowing through these large hydro power plants because they represent a much larger share of the power generation in Colombia.

[1] 14 years times 12 months equal to 168 values
[2] During the years
[3] In Colombia, large power plants refers to power plants with a rated capacity of 20MW or more

		Rated capacity [MW]	Share
Centrally dispatched (≥ 20MW)	**Hydraulic**	10.335	66,6%
	Thermal	4.410	28,4%
Not centrally dispatched (< 20MW)	**CHP[1]**	82,2	0,5%
	Wind	18,42	0,1%
	Hydraulic	584,88	3,8%
	Thermal	91,35	0,6%
Total installed capacity		15.521,85	100%

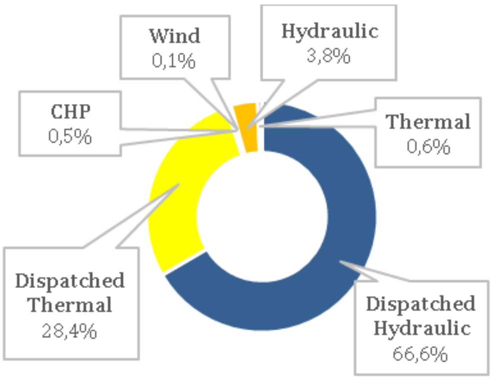

Table 10: Current installed power capacity in Colombia. XM [3]

On one side, there is information about river in-inflows in Colombia. Historic monthly in-flows[2] of 25 rivers were made available by XM from the year 2000 until 2014 [45]. From the 25 rivers, 24[3] are flowing through the centrally dispatched hydro power plants. Thus, in-flows of 24 rivers distributed all over the country are considered for this study. Although there is information about the in-flows from the year 2000, some projects have entered in operation between 2000 and 2014. As a result, there are rivers with less information than others. Furthermore, only the data covering a full year are considered. Besides that, as the Stream 3 of MERRA comprises the years 2001 to 2014 from the wind and solar resource, in-flows of the year 2000 are neglected in order to have the same time span for the analyses. An artificial *national conglomerate* was also built for the years 2002 to 2014. This because two rivers have no data for 2001[4]. In total, 21 rivers of the 24 flowing through the centrally dispatched power plants were grouped in the national conglomerate[5].

On the other side, information about the power plants was also gathered. From the 25 large hydro power plants listed by XM, information about the rivers flowing through five[6] of them was not found and one[7] entered in operation in December 2014. Therefore, 19 large hydro power plants are considered for this study. However, the power plant that entered to the system in December 2014 and three[8] other future large power plants [13] are also mentioned because the results of places nearby might give a first approximation of the expected values.

Consequently, as to adequately select which rivers flow to which hydro power plants, the generation chains were analysed based on the developed by the UPME in 2014 [46]. An example of these generation chains is shown in the Appendix 11.13. Furthermore, information about the hydrography in Colombia was also reviewed and the rivers tracked for double-check with a

[1] Combined Heat and Power / Cogeneration
[2] “Aportes” in the web site
[3] The river Florida II flows through a hydro power plants smaller than 20MW. Thus, it is not considered
[4] Porce II and Urrá
[5] Amoyá, Miel I and Porce III were not include because of the lack of data for several years
[6] Dario Valencia Samper, El Popal, Esmeralda, Salto II and San Francisco
[7] Sogamoso (820MW)
[8] Quimbo (400MW), Porvenir II (354MW), Ituango (2.400MW)

Geographical Information System (GIS) developed by the IDEAM (Institute of Hydrology, Meteorology and Environmental Studies of Colombia) and SiGaia, a Colombian company with experience in the systematization of geographic information, [47]. As a result, the rivers feeding each power plant were identified and the locations within the country were plotted in ©Google Earth. Finally, in-flows for the 168 months of the 14 years were organized.

4.6 Estimates of energy generation

For the energy analyses, the meteorological resources are transformed into wind-, solar- and hydroelectric energy, as described in the following sub-sections. A monthly analysis is executed due to the resolution of the hydro data. Based on the report published by the UPME [13] this year, the best scenarios for renewable energy consider 1.370 MW of wind power and 239,2 MW of solar power. As a consequence, as to have different wind parks and not only a large one, a rated capacity of 99 MW is proposed for each wind site. For the solar farms, a rated capacity of 50MWp is proposed for each solar site. For the hydro sites, the rated capacities of the existing hydro power plants are taken as they are. Following, the information which is assessing the Pearson´s correlation coefficient for the energy generation:

	Quantity of power plants	Nominal Power (NP) of each power plant	Values in the assessment of the Pearson´s coefficients	
			Variable	Units
Wind energy	13	99 MW	Monthly wind energy production	[GWh/month]
Solar energy	14	50 MWp	Monthly solar energy production	
Hydroelectric energy	19	Please see Table 17	Monthly hydroelectric energy production	

Table 11: Variables for assessing the Pearson´s coefficients between sites for energy production

It is necessary to remind the reader here that the technical characteristics of the transmission grid in the country are not addressed in this study. As a result, an ideal transmission grid with enough capacity for all the projects is assumed. Furthermore, as before, the 168 monthly energy generations for each wind, solar and hydro site were calculated.

Wind energy: The energy production for the wind parks was assessed in these steps:

- **Selection of wind turbine:** The manufacturer with the largest share in Latin America, Vestas [48], a Danish company, was selected. Within its portfolio, the turbine V126 3,3MW [49](3,3MW rated capacity; a 100m hub height was assumed[1]) was chosen due to the access to its power curve through a confidential agreement with the German wind power developer Notus energy GmbH (from now onwards, “Notus”). Although the selection of a turbine depends on many site-related-factors, this study uses the same turbine for all the sites for simplification. For a 99MW wind park, 30 turbines are used for each site.

[1] For modern turbines, several hub height are available. 100m was chosen for being a common height for different turbines.

- **Extrapolation of wind speeds to 100m:** Hourly wind speeds @ 50m from MERRA were extrapolated to hourly wind speeds @ 100m calculated with the logarithmic wind profile with neutral stratification[1] [50]was used:

$$u(z) = \frac{u_*}{k} ln \frac{z-d}{z_0}$$

Equation 7: Logarithmic wind profile with neutral stratification

Where u refers to wind speed at the z desired height, u_* to the friction velocity, k to the van Kármán constant, d to the displacement height and z_0 to the roughness length. However, if we divide the Equation 7 for two different heights, we get:

$$\frac{u(z_{100})}{u(z_{50})} = \frac{\frac{u_*}{k} ln \frac{z_{100}-d}{z_0}}{\frac{u_*}{k} ln \frac{z_{50}-d}{z_0}} \qquad resulting\ in \qquad u(z_{100}) = u(z_{50}) \frac{ln\left[\frac{z_{100}}{z_0}\right]}{ln\left[\frac{z_{50}}{z_0}\right]}$$

Equation 8: Extrapolation of wind speeds @ 50m to @ 100m with a zero displacement height

The MERRA variable DISPH refers to the displacement height d. Nevertheless, this study considers a displacement height of zero because, as a regional analysis, there might be areas within the MERRA grid box with several different topographies. The roughness length z_0, represented by the MERRA variable Z0M, might have been taken as one constant value. However, with the aim of considering different roughness lengths cause by seasonal crops throughout the year, mean monthly roughness lengths were calculated.

- **Binning wind speed data:** For every month of the 14 years, the hourly wind speeds @100m were aggregated in a histogram of 50 bins. Each of the bins[2] has a width of 0,5m/s. The quantity of bins was selected because the power curve used has the same binning.
- **Power production of a single turbine:** The quantity of each bin of the wind speeds @ 100m for that month was multiplied by the power produced by the wind turbine in the same bin as to generate the monthly energy generation.

- **Density correction:** The power change is considered proportional to the air density [51]. Similar to the roughness lengths, monthly average of the air density were calculated for every month of all the 14 years for each site. Then, since the standard power curve of the wind turbine has an air density of 1,225 kg/m^3, the monthly power produced was multiplied by the proportion between the monthly air density calculated and the standard air density as to correct it.

[1] For knowing the kind of stratification (stable, neutral or unstable) on the atmospheric boundary layer of a site, micro-scale data is need. As this is a regional study, a general neutral stratification is assumed
[2] The bin number 1 has values from 0 to 0,75 m/s. However, as multi MW wind turbines do not produce energy in these wind speeds, this longer width is of no relevance

- **Power production of the wind park:** As a 99MW wind park is evaluated, the monthly production of the single turbine was multiplied by 30. Furthermore, the following losses – based on the experience of Notus with a wind park of this size - were subtracted from these monthly values as the get the net monthly energy production:

	Estimated losses for a 99 MW wind park
Wake losses	4,7 %
Losses for turbines availability	4 %
Grid losses	4 %
Power curve losses	3%

Table 12: Estimated losses for a 30 x 3,3 MW wind park based on the experience of the German wind power developer Notus

Solar energy: The energy production for the solar parks was calculated as described below:

The monthly solar energy was calculated based on the Ostwald's method, described in the paper published by Almonacid et al. in 2011 [52] as the most used for estimating the power provided from a PV (Photovoltaic) solar park. The expressions is presented in the following equation:

$$Monthly\ solar\ energy: SE_{month,year}[GWh] = NP[MW_p] * \frac{\sum_{hour=1}^{hours\ month} SWGDN_{hour,month,year}\left[\frac{W}{m^2}\right]}{G_{STC}\left[\frac{W}{m^2}\right]} * 1000 * PR * \eta_T$$

Equation 9: Model for assessing the monthly production of a solar farm for a specific month of a specific year

Where the nominal power NP is $50\,MW_p$, $SWGDN_{hour}$ is the MERRA hourly solar surface incident shortwave flux during a specific month of a specific year. The performance ratio without considering temperature $\boldsymbol{PR}$[1] **is considered as 0,82** assuming an optimal system in Colombia (taken from the paper about solar systems in Colombia written in 2014 by Mulcué-Nieto and Mora-López [53]). The irradiance at Standard Test Conditions G_{STC} is equal to $1.000\frac{W}{m^2}$. Furthermore, the temperature losses η_T are calculated as follows:

$$Temperature\ losses: \eta_T = 1 - \gamma\left[\frac{1}{°C}\right] * (T_{C\ hour}[°C] - 25[°C])$$

Equation 10: Temperature losses

The **temperature coefficient $\boldsymbol{\gamma}$** was taken from the data sheet of two different modules[2] from the leading solar module supplier in Latin America [54], Yingli Solar, as 0,42 $\frac{\%}{°C}$. $T_{C\ hour}$ refers to the hourly cell module temperature which is assessed with the equation below:

[1] Factor depending on how well the PV system performs. It is affected by several inputs. Please refer to Appendix 11.16
[2] Either the polycrystalline YGE 60 cell series 2 [102] or the monocrystalline Panda 60 cell series 2 [103]. These two solar modules have the same γ and $NOCT$

$$Hourly\ cell\ module\ temperature:\ T_{C\ hour}[°C] = T_{A\ hour}[°C] + SWGDN_{hour}\left[\frac{W}{m^2}\right] * \frac{NOCT[°C] - 20[°C]}{G_{NOCT}\left[\frac{W}{m^2}\right]}$$

Equation 11: Hourly cell module temperature

The hourly ambient temperature $T_{A\ hour}$ was taken directly [1] from the MERRA hourly temperature at 2m above the displacement height $T2M_{hour}$ in $°C$. $T_{C\ hour}$ also depends on the Nominal Operating Cell Temperature $NOCT$, taken as 46 $°C$ from the Yingli Solar modules and its irradiance G_{NOCT}, set as 800 $\frac{W}{m^2}$.

Hydroelectric energy: The energy production for the hydro power plants was calculated as described below:

The steps for calculating the hydroelectric energy in this study refer to a simplification based on local data from XM. As shown in Table 17, XM provides a conversion factor CF for each of their hydro power plants. These factors state the power generated by a power plant thanks to an in-flow of a river (or compound of rivers), when the dam is within levels of normal operation [55]. As a result, the monthly hydroelectric energy HE of a hydro power plant HPP was calculated for every month for all the years as follows:

$$HE_{month,year,HPP}[GWh] = In\_flow_{month,year,HPP}\left[\frac{m^2}{s}\right] * CF\left[\frac{MW}{\frac{m^2}{s}}\right] * Hours_{month,year}[h] * \frac{1}{1000}$$

Equation 12: Assessment of the monthly hydroelectric energy HE of a hydro power plant HPP with conversion factor CF for a specific month of a specific year

4.7 Intra-annual and inter-annual complementarity

This study relates the complementarities with the Pearson´s correlation coefficient for the meteorological resources and for the energy productions. As to calculate the correlation coefficients, four parameters are set:

- **The temporal resolution is on a monthly basis:** Seasonal changes on the hydrology can be easily observed on a monthly basis. As rivers do not have strong variations on hourly or daily basis. Thus, river in-flows were download on a monthly basis. For the wind and solar sites, the hourly data was converted into monthly data as explained previously.

- **The coefficients are calculated between the hydro-wind and the hydro-solar resource and power plants:** Considering the large share of hydro power in Colombia and the availability of water resources due to its rich mountainous orography, the country can and should take advantage principally from the hydro resource. Therefore, the analysis

[1] Although the variable T2M of MERRA refers to the Temperature at 2m above the displacement height, these displacement heights were neglected and thus, these temperature are taken as temperatures at 2m above surface. This because the grid points represent such as large area (~74,2m x ~55,3km) and the displacement heights vary very much inside an area like this due to the local orography and roughness of the terrain

considers the hydro resource as the base and correlations are made between it and the wind resource, on one side, and the solar resource, on the other side. This, similar to a complementarity study made by de Jonh et al. in 2013 for the northeast of Brazil [56]. As other interesting global approaches such as the one made by Gerlach et al. in 2011 [51], no complementarities between wind and solar are presented in this study. As a result, the monthly in-flows of the 24 rivers plus the national group are compared to the monthly wind speeds @50m from the 13 wind sites and to the monthly solar surface insolation from the 14 solar sites. Similarly, the monthly energy production of the 19 hydro power plants are compared with the monthly generation of the 13 wind parks and to the 14 solar parks simulated.

- **All-against-all analysis:** An attempt of clustering[1] the mean normalized monthly curves of the data was executed. However, due to the wide possibility of obtaining different clusters and the time required for defining their parameters for doing it, it was preferred to use the curves of all the sites. Thus, all hydro sites are calculated against all the wind sites. This generates the hydro-wind matrix of coefficients. Consequently, the same process is carried out with the solar sites and the hydro-solar matrix is obtained.

- **Correlation coefficients for every year:** For the intra-annual complementarity, the coefficients for every year (2001-2014), based on the 12 months of each year, were assessed and, afterwards, the means of these 14 coefficients were obtained[2]. For the inter-annual complementarity, there are only 14 values based on annual values of the 14 years. As a result, there is only on coefficient for each pair compared. These values are the ones exhibited in the results.

No Pearson´s coefficients were calculated for the normalized values. The coefficients between real values and between normalized values are equal. This is demonstrated in the Appendix 11.15.

4.8 Annual resource- and energy indexes and IAV

An index refers to a set of fluctuations of any kind of resource or of the generated energy that a power plant has experienced. This expression is based on a historical temporal span which is used as reference [57] and is the most common form for estimating a long-term value. Several indexes have been developed in different countries (starting in Denmark in 1979), most of them related to energy production of wind parks. Countries like Germany, Sweden and the Netherland have worked on their own Wind Indexes and probably the most well-known is the German IWET[3] where 22.000 different wind turbines have been considered in the data base [58]. These are based in production data and wind data in situ and for long-term sources like

[1] Automatic clustering done by ©Matlab with function *clusterdata*
[2] If there was less years with data, then lesser coefficients could be calculated
[3] Windindes der Ingenieurwerkstatt Energietechnik

Reanalysis. However, as there are not enough wind and solar parks in Colombia, meaning a lack of production data, the indexes presented in this study are merely based on MERRA data. Much more accurate indexes could be developed based on production data and in situ measurements as described in a study carried out by Rimpl and Westerhellweg [58] in 2013, where the development of a wind index for Brazil was thoroughly presented. Novel approaches can also be consulted in discussion paper published by Ritter et al. in 2015 [59] where a wind index for Germany is directly calculated for a certain wind turbine, from production data, without doing the step of calculating wind speeds in between.

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For the **MERRA-based wind and solar resource indexes** in this study, the temporal span for the indexes is 2001-2014, 14 years. They are based on the mean annual wind speeds @ 50m for the wind resource and on the mean annual solar surface insolation for the solar resource. The 100% values showed there represents the calculated mean wind speed @50m and mean solar surface insolation for each site within the temporal span. For the MERRA-based wind and solar energy indexes, the Annual Energy Production (AEP) of every year for each power plant are the base of the calculations. Similarly, the 100% value exhibited there, represents the mean AEP within these years.

The same for the river in-flows from XM was applied. The temporal span is also 2001-2014. And they are based on mean river in-flows within these years. For the XM-based hydro resource index, the 100% value corresponds to the calculated mean annual river in-flow for each river. For the XM-based energy index, the 100% values refers to the assessed mean AEP of each hydro power plant along these years.

IAV (Inter-Annual Variability)

The IAV (Inter-Annual Variability) is defined as the standard deviation of the annual means divided by the overall mean. Both for the averages of the resource and the energy production for each year. This represents how variable is the resource or the energy production from one year to other [60].

5 Meteorological results

5.1 Meteorological resources and annual resource indexes

5.1.1 Wind resource and selected wind sites

The sites were named based on the regions were the MERRA grid points are located and represent the average values of the area covered by the grid point. The locations, from south (top) to north (bottom), are given by the coordinates -longitude and latitude- with the signs explained in the section 4.1. Based on hourly data for the 14 years, their mean wind speeds

@50m, surface air density and roughness length as well as their constant height above sea level given by MERRA are exhibited in Table 13. The mean wind speed is plotted in the Figure 7.

	Name	Long. [°]	Lat. [°]	Mean wind speed @ 50m [m/s]	Mean surface air density [kg/m^3]	Mean roughness length [m]	Height above sea level [m]
1	**Nariño**	-77,33	+1	3,73	0,923	0,07	2.456
2	**Pacífico Sur**	-78,66	+2	3,90	1,166	0,03	9
3	**Buenaventura Sur**	-77,33	+3,5	4,53	1,156	0,03	101
4	**Tolima**	-75,33	+3,5	3,58	1,031	0,07	1.230
5	**Cundinamarca**	-74	+4,5	3,83	0,931	0,07	2.351
6	**Casanare**	-72	+4,5	3,34	1,146	0,06	165
7	**Boyacá**	-73,33	+5,5	3,29	0,912	0,19	2.557
8	**Arauca**	-70,66	+6,5	3,43	1,151	0,06	119
9	**Norte de Santander**	-72,66	+7,5	4,41	0,973	0,07	1.886
10	**Córdoba**	-76,66	+9	3,31	1,160	0,29	2
11	**Atlántico**	-75,33	+11	6,18	1,159	0,20	2
12	**Guajira**	-72	+12	7,66	1,158	0,05	28
13	**San Andrés**	-82	+12,5	7,38	1,162	0,07	0

Table 13: Selected wind sites and their mean values based on hourly data from the Stream 3 of MERRA (2001-2014)

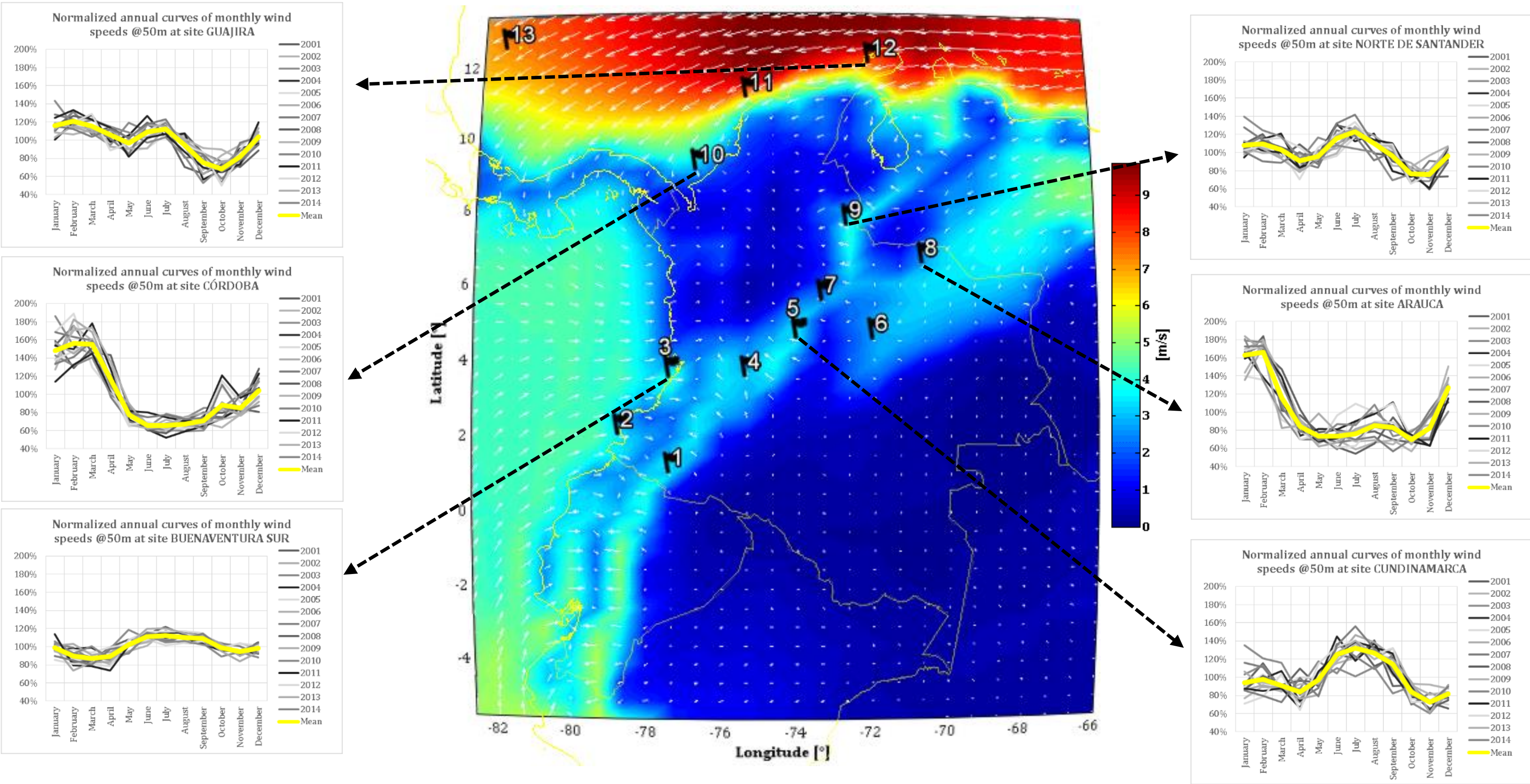

Figure 7: Mean wind speed[1] @50m in [m/s] based on hourly data from the Stream 3 of MERRA (2001-2014) and 13 selected wind sites (black flags) with the normalized monthly curves[2] of the wind speed for 6 of the 13 sites. The white arrows represent the magnitude (also represented by colours) and direction of the wind. Projected in © Google Earth

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[1] An interpolation was executed in Matlab only for visual purposes. However, the real resolution of the data is as state in the section 4.1and is shown in Figure 37 in the Appendix 11.2
[2] The normalized curves of all sites are exposed with a better resolution in the Appendix 11.6

The normalized-with-the-average-of-each-year monthly curves of the wind speed @ 50m for 6 of the 13 wind sites are also presented in the Figure 7 as to have an overview of the multiplicity of patterns within the country along the year. With the aim of reducing the quantity of wind sites and recognising these regional patterns, an automatic clustering in Matlab was attempted. However, as the monthly behaviours of the wind speeds @ 50m vary considerably among the wind sites, this clustering was not easy to carry on and, as a result, all the 13 wind sites were considered for the complementarity analyses. As to illustrate it, a 3-groups-custering is shown in the Figure 8.

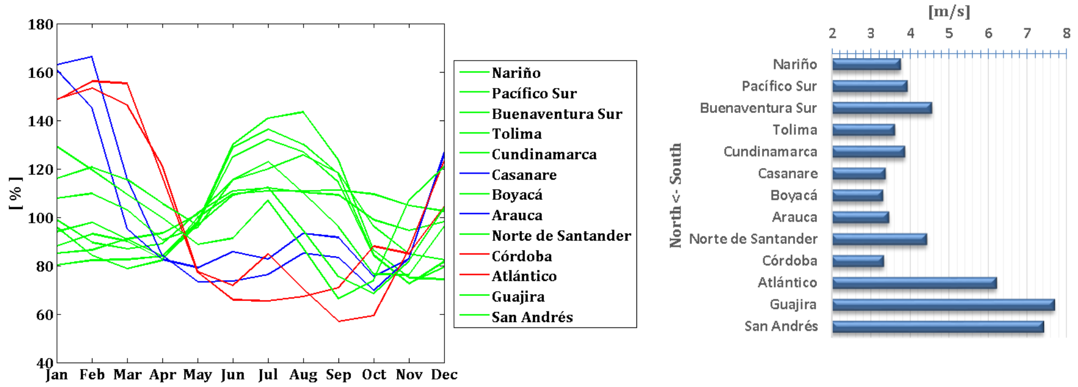

Figure 8: (Left) 3-groups-clustering executed on © Matlab showing the monthly behaviour of the mean wind speeds @ 50m of the 13 selected wind sites and (Right) their mean wind speeds @50m, presented from south to north[1], from 2001 to 2014

As described in the section 4.8, the MERRA-based wind resource indexes were calculated for each of the 13 wind sites for all the 14 years and are presented in the Table 14 along with their IAVs (Intern-Annual Variability). The 100% value corresponds to the average of the hourly wind speeds @ 50m from MERRA for the specific wind site with the reference period 2001-2014. The bluest values refer to the highest indexes, consequently the years with highest mean wind speeds; the reddest values the lowest, representing years with the lowest means. The values presented here can also be graphically observed in the figures of the Appendix 11.6.

		Mean wind speed @50m [m/s]	MERRA-based wind resource index														IAV
		100%	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
North <- South	Nariño	3,73	107%	109%	110%	107%	106%	109%	98%	92%	93%	85%	87%	101%	93%	104%	8,4%
	Pacífico Sur	3,90	102%	100%	103%	99%	102%	97%	104%	97%	100%	101%	96%	95%	103%	104%	2,9%
	Buenaventura Sur	4,53	103%	99%	100%	100%	102%	97%	104%	99%	103%	99%	94%	97%	101%	104%	2,9%
	Tolima	3,58	102%	103%	106%	103%	104%	103%	99%	93%	100%	95%	92%	102%	97%	102%	4,0%
	Cundinamarca	3,83	107%	110%	103%	103%	102%	103%	100%	93%	103%	87%	88%	99%	97%	106%	6,6%
	Casanare	3,34	100%	106%	102%	108%	106%	100%	105%	98%	95%	90%	98%	98%	97%	97%	4,7%
	Boyacá	3,29	106%	110%	102%	103%	103%	103%	100%	94%	103%	87%	88%	99%	96%	105%	6,3%
	Arauca	3,43	99%	104%	100%	106%	103%	101%	104%	105%	98%	86%	94%	99%	100%	101%	4,9%
	Norte de Santander	4,41	109%	114%	100%	102%	95%	102%	100%	96%	105%	87%	87%	98%	101%	105%	7,2%
	Córdoba	3,31	103%	103%	99%	108%	104%	98%	98%	103%	103%	106%	96%	92%	94%	93%	4,8%
	Atlántico	6,18	105%	111%	96%	108%	93%	101%	101%	103%	108%	87%	89%	97%	99%	101%	6,7%
	Guajira	7,66	110%	112%	103%	102%	88%	101%	97%	96%	107%	84%	88%	98%	104%	111%	8,5%
	San Andrés	7,38	106%	109%	97%	106%	92%	100%	95%	98%	107%	94%	92%	101%	97%	106%	5,7%

Table 14: MERRA-based wind resource indexes with their IAVs of the 13 selected wind sites

[1] Depending on their locations within the country

5.1.2 Solar resource and selected solar sites

14 solar sites were selected based on the criteria described in the section 4.4 and are presented in the Table 15 and in the Figure 9. As for the wind sites, the solar sites were named based on the regions were the MERRA grid points are located and represent the average values of the area covered by the grid point. Solar sites with the same name of the wind sites refer to the same grid point. They are also presented from south (top) to north (bottom). Based on hourly data for the 14 years, their mean annual solar surface insolation[1] are listed in the table and shown in the Figure 10. Temperatures at 2m above the surface are also presented. Two different temperatures are presented: the mean temperature, which considers day and night, and the mean temperature during day, which considers exclusively hours with solar irradiation – the ones which are affecting directly the solar power generation. The constant heights above sea level given by MERRA are also exhibited.

	Name	Long. [°]	Lat. [°]	Mean annual solar surface insolation [kWh/m²/year]	Mean daily solar surface insolation [kWh/m²/day]	Mean temp. [°C]	Mean temp. during day [°C]	Height above sea level [m]
1	**Nariño Sur**	-78	+1	2.082	5,70	16,34	18,67	2.110
2	**Cauca**	-76,66	+3	2.057	5,64	19,30	21,46	1.558
3	**Huila**	-75,33	+3	2.105	5,77	20,25	22,21	1.331
4	**Cundinamarca Occidente**	-74,66	+4,5	2.175	5,96	22,02	24,26	1.292
5	**Casanare**	-72	+4,5	1.695	4,64	26,30	27,26	165
6	**Boyacá**	-73,33	+5,5	2.092	5,73	13,62	15,40	2.557
7	**Antioquia**	-75,33	+6,5	1.875	5,14	17,64	18,68	1.796
8	**Arauca**	-70,66	+6,5	1.645	4,51	26,25	27,54	119
9	**Norte de Santander**	-72,66	+7,5	2.096	5,74	17,10	18,82	1.888
10	**Bolivar**	-74	+9	1.733	4,75	26,94	27,64	128
11	**Cesar**	-73,33	+10	1.939	5,31	24,36	26,14	603
12	**Atlántico**	-75,33	+11	1.833	5,02	28,08	28,53	2
13	**Guajira**	-72	+12	1.908	5,23	27,62	29,23	28
14	**San Andrés**	-82	12,5	1.845	5,05	27,87	27,90	0

Table 15: Selected solar sites and their mean values based on hourly data from the Stream 3 of MERRA (2001-2014)

The normalized monthly curves of the surface solar insolation for 6 of the 14 solar sites are also presented in the Figure 9 as to show the diversity of patterns within the country along the year. Similarly for the wind sites, a clustering was done without clear outcomes due to very different monthly behaviours of the solar surface insolation among the solar sites. As to illustrate it, a 3-groups-custering is shown in the Figure 10. Consequently, all the 14 solar sites were considered for the complementarity analyses.

[1] The mean daily solar surface insolation is calculated diving by 365 days

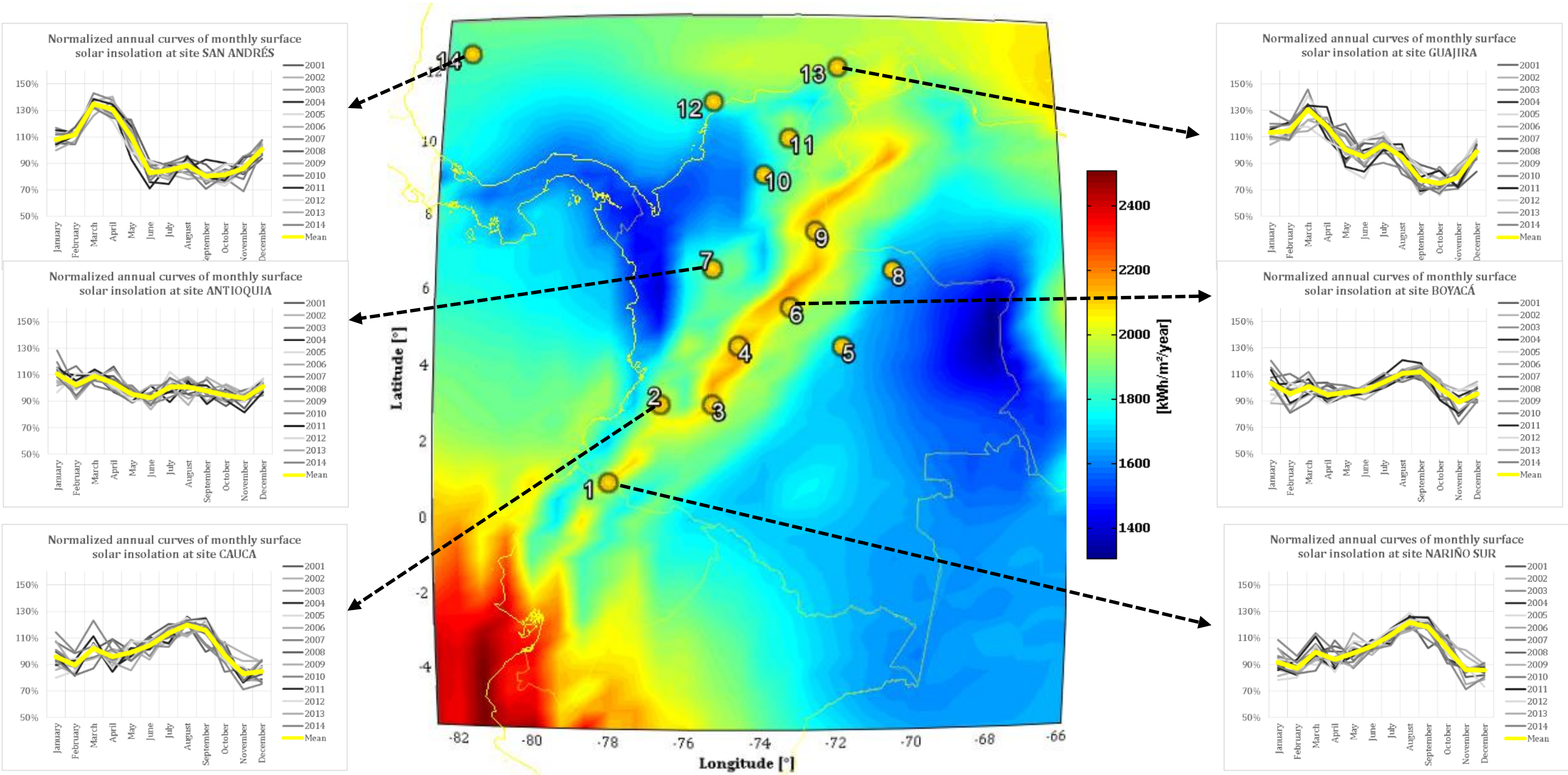

Figure 9: Mean annual solar surface insolation¹ in [kWh/m²/year] based on hourly data from the Stream 3 of MERRA (2001-2014) and 14 selected solar sites (yellow circles) with the normalized monthly curves² of the surface solar insolation for 6 of the 14 sites. Projected in © Google Earth

¹ An interpolation was executed in Matlab only for visual purposes. However, the real resolution of the data is as state in the section 4.1 and is shown in Figure 38. An annual insolation of 2.400 $kWh/m^2/year$ is approx. equal to a daily insolation of 6,6$kWh/m^2/day$. Respectively, 1.400 $kWh/m^2/year$ represents approx. 3,8 $kWh/m^2/day$
² The normalized curves of all sites are exposed with a better resolution in the Appendix 11.7

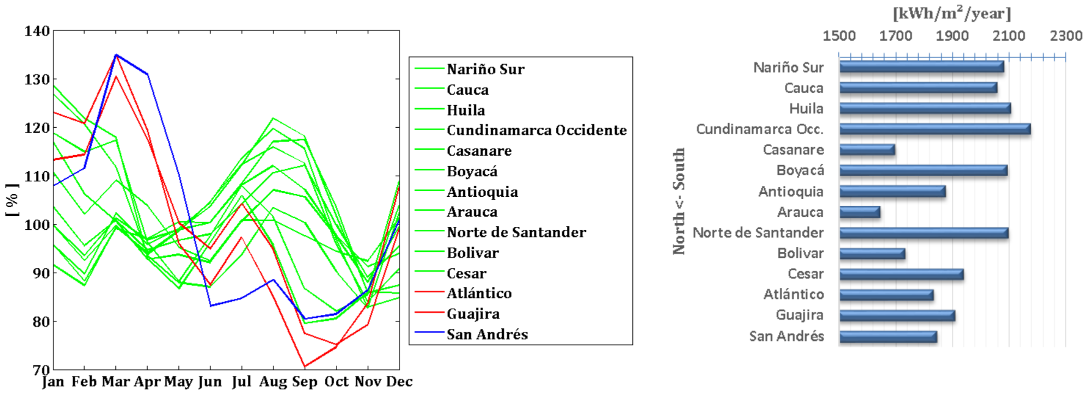

Figure 10: (Left) 3-groups-clustering executed on © Matlab showing the monthly behaviour of the mean surface solar insolation of the 14 selected solar sites and (Right) their mean annual surface solar insolations, presented from south to north[1], from 2001 to 2014

As described in the section 4.8, the MERRA-based solar resource indexes were calculated for each of the 14 solar sites for all the 14 years and are presented in the Table 16 along with their IAVs. The 100% value corresponds to the mean annual solar surface insolation from MERRA for the specific solar site with the reference period 2001-2014. The bluest values refer to the highest indexes, consequently the years with highest mean solar insolation; the reddest values the lowest, representing years with the lowest means. The values presented here can also be graphically observed in the figures of the Appendix 11.7.

North <- South	Mean annual solar surface insolation [kWh/m²/year]	MERRA-based solar resource index														IAV
	100%	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
Nariño Sur	2.082	104%	102%	105%	101%	100%	100%	100%	95%	101%	94%	93%	99%	102%	105%	3,6%
Cauca	2.057	107%	106%	105%	101%	102%	102%	102%	96%	99%	91%	92%	97%	98%	103%	4,8%
Huila	2.105	104%	103%	105%	100%	102%	102%	103%	95%	101%	95%	91%	97%	99%	103%	3,8%
Cundinamarca Occ.	2.175	108%	109%	107%	103%	105%	103%	102%	98%	98%	90%	89%	96%	93%	99%	6,2%
Casanare	1.695	102%	104%	107%	99%	101%	100%	102%	99%	96%	93%	95%	100%	99%	104%	3,7%
Boyacá	2.092	106%	107%	103%	100%	101%	98%	103%	98%	102%	95%	93%	99%	97%	99%	3,8%
Antioquia	1.875	107%	109%	103%	105%	104%	105%	102%	101%	96%	89%	92%	96%	94%	97%	5,7%
Arauca	1.645	96%	100%	101%	100%	99%	98%	102%	104%	97%	95%	98%	103%	102%	106%	3,1%
Norte de Santander	2.096	104%	103%	100%	98%	99%	99%	101%	101%	101%	97%	97%	101%	100%	100%	2,0%
Bolivar	1.733	100%	107%	98%	102%	100%	103%	101%	104%	99%	91%	98%	99%	95%	104%	3,9%
Cesar	1.939	100%	105%	97%	100%	100%	101%	100%	103%	101%	92%	97%	100%	99%	105%	3,2%
Atlántico	1.833	101%	105%	94%	98%	97%	100%	98%	106%	103%	93%	98%	99%	101%	108%	4,3%
Guajira	1.908	101%	102%	98%	100%	98%	101%	98%	102%	103%	91%	97%	99%	103%	107%	3,6%
San Andrés	1.845	102%	99%	96%	101%	95%	101%	98%	101%	101%	97%	103%	103%	102%	102%	2,5%

Table 16: MERRA-based solar resource indexes with their IAVs of the 14 selected solar sites

5.1.3 Selected rivers and hydro power plants

As explained in the section 4.5, 24 rivers feeding 19 large hydro power plants were selected. Both the rivers and the power plants are listed from south (top) to north (bottom) in the Table 17 for having a better overview. Their locations are presented in the Figure 11. Four future/recent projects are also included in the table. Some power plants took the name of their rivers. The normalized monthly curves of the in-flows for 6 of the 24 rivers are also presented

[1] Depending on their locations within the country

in the Figure 12 as to show the variety of the patterns within the country along the year. As for the wind/solar sites, a clustering was executed without clear outcomes due to variety of patterns. Consequently, all the 24 rivers were considered for the complementarity analyses. As to illustrate it, a 3-groups-custering is shown in the. There the national ensemble can be observed as a yellow line.

					Rivers flowing through				
Hydro power plant	Rated capacity [MW]	Type	Conversion factor [MW/m³/s]	Dam capacity [million m³]	Name of river	Mean in-flow [m³/s]	Years with data from/to [y]		
Quimbo	400	Dam	-	-	-	-	Start in 2015		-
Betania	540	Dam	0,6236	1.981	**Magdalena Betania**	414,58	2001	2014	14
Salvajina	285	Dam	0,9928	906	**Cauca Salvajina**	127,40	2001	2014	14
Alban	429	Dam	3,9055	50	**Alto Achincayá**	46,10	2001	2014	14
					Digua	28,86	2001	2014	14
Calima	132	Dam	1,8712	581	**Calima**	11,71	2001	2014	14
Amoyá	80	Run-of-the-river	4,8664	0	**Amoyá**	15,32	2014	2014	1
Prado	51	Dam	0,4916	966,22	**Prado**	57,13	2001	2014	14
Pagua	600	Run-of-the-river	16,573	0	**Bogotá N,R,**	30,94	2001	2014	14
					Chuza	10,23	2001	2014	14
Guavio	1.213	Dam	9,7433	1.043	**Guavio**	68,57	2001	2014	14
Chivor	1.000	Dam	7,0123	569,64	**Batá**	78,10	2001	2014	14
Miel I	396	Dam	2,0092	571	**Miel I**	94,51	2003	2013	11
Porvenir II	352	Dam	-	-	-	-	Start in 2018		-
San Carlos	1.240	Dam	5,4694	72	**San Carlos**	27,48	2001	2014	14
					Guatapé	36,31	2001	2014	14
					Nare	51,08	2001	2014	14
					A, San Lorenzo	40,65	2001	2014	14
Playas	207	Dam	1,5605	50,29	**Guatapé**	36,31	2001	2014	14
					Nare	51,08	2001	2014	14
					A, San Lorenzo	40,65	2001	2014	14
Guatapé	560	Dam	7,6711	1071	**Nare**	51,08	2001	2014	14
Jaguas	170	Dam	2,5517	185,5	**A, San Lorenzo**	40,65	2001	2014	14
Tasajera	306	Dam	7,7642		**Grande**	32,70	2001	2014	14
Guatron	512	Dam	8,315		**Guadalupe**	22,13	2001	2014	14
					Concepción	6,76	2001	2014	14
					Tenche	4,52	2001	2014	14
					Desv, EEPPM (Nec, Paj, Dol)	8,02	2001	2014	14
Porce II	405	Dam	2,23	142,7	**Grande**	32,70	2001	2014	14
					Porce II	98,32	2002	2014	13
Porce III	700	Dam	3,1723	169	**Guadalupe**	22,13	2001	2014	14
					Concepción	6,76	2001	2014	14
					Tenche	4,52	2001	2014	14
					Desv, EEPPM (Nec, Paj, Dol)	8,02	2001	2014	14
					Porce III	23,39	2011	2014	4
Ituango	2.400	Dam	-	970	-	-	Start 2018-22		-
Sogamoso	820	Dam	-	4.800	-	-	Start in 2014		-
Urrá	338	Dam	0,4471		**Sinú Urrá**	334,67	2002	2014	13
National[1]	7970	-	-	-	**21 of 24 rivers**	1550,80	2002	2014	13

Table 17: Characteristics of the 19 large hydro power plants and their 24 rivers. The four shaded names correspond to the four future/recent projects

[1] This aggregates 16 hydro power plants considering 21 rivers from 2002 to 2014 as to include some rivers with had values only from 2002 onwards. The 21 rivers are: Magdalena Betania, Cauca Salvajina, Digua, Alto Anchicayá, Calima, Prado, Bogotá N.R., Chuza, Guavio, Batá, San Carlos, Guatapé, Nare, A. San Lorenzo, Grande, Guadalupe, Concepción, Tenche, Desv. EEPPM (Nec, Paj, Dol), Porce II, Sinú Urrá. Not included: Amoyá, Miel I and Porce III due to lack of data for some years

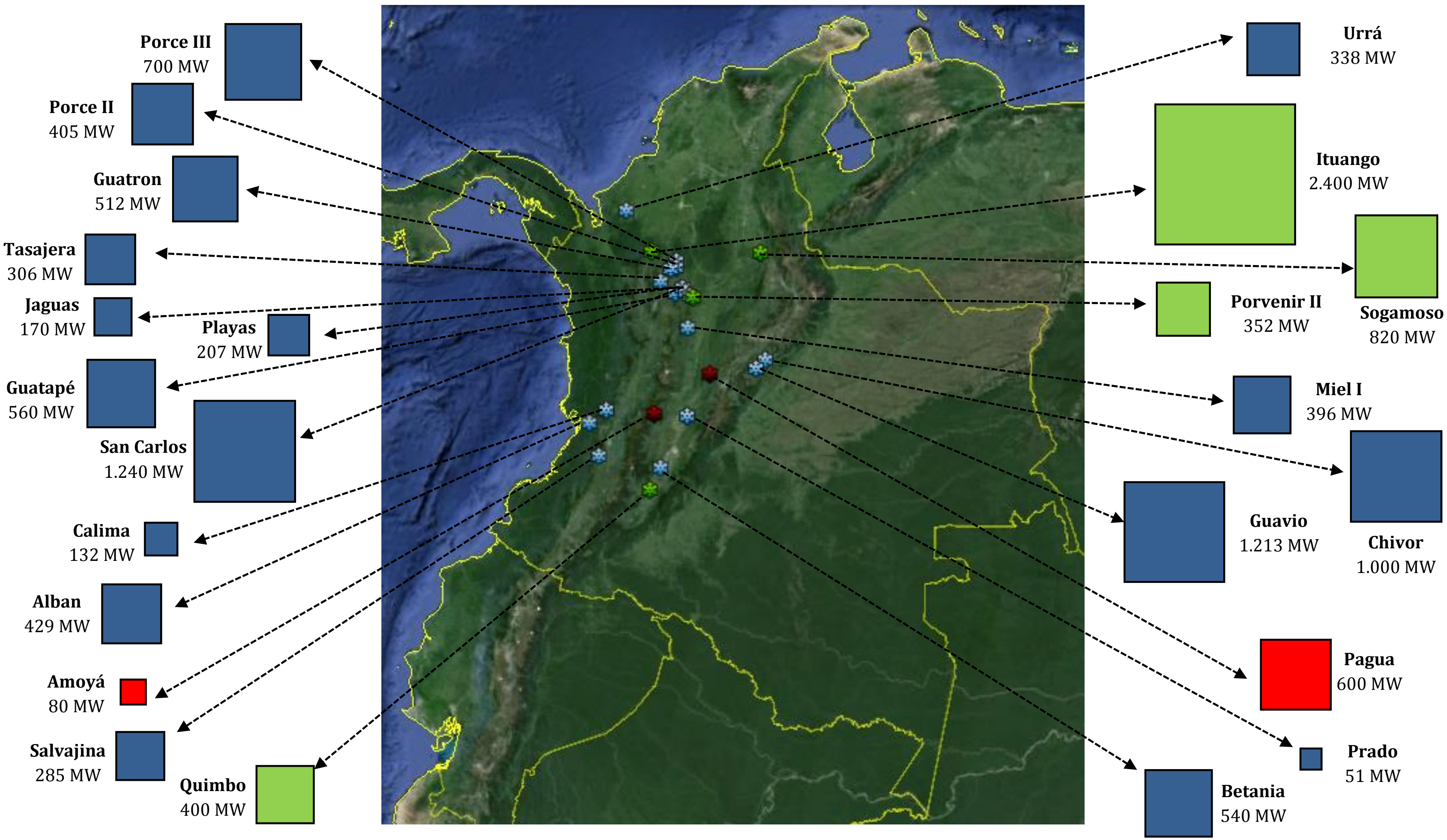

Figure 11: Location and rated capacity (proportional to the area of the square) of the large hydro power plants considered in this study. Blue: current dam-power plants. Red: current run-of-the-river power plants. Green: future/recent dam-power plants. Projected in © Google Earth

Figure 12: Location of the selected rivers (blue points) and normalized monthly curves[1] of the in-flow for 6 of the 24 rivers Projected in © Google Earth

[1] The normalized curves of the river in-flows are exposed with a better resolution in the Appendix 11.8

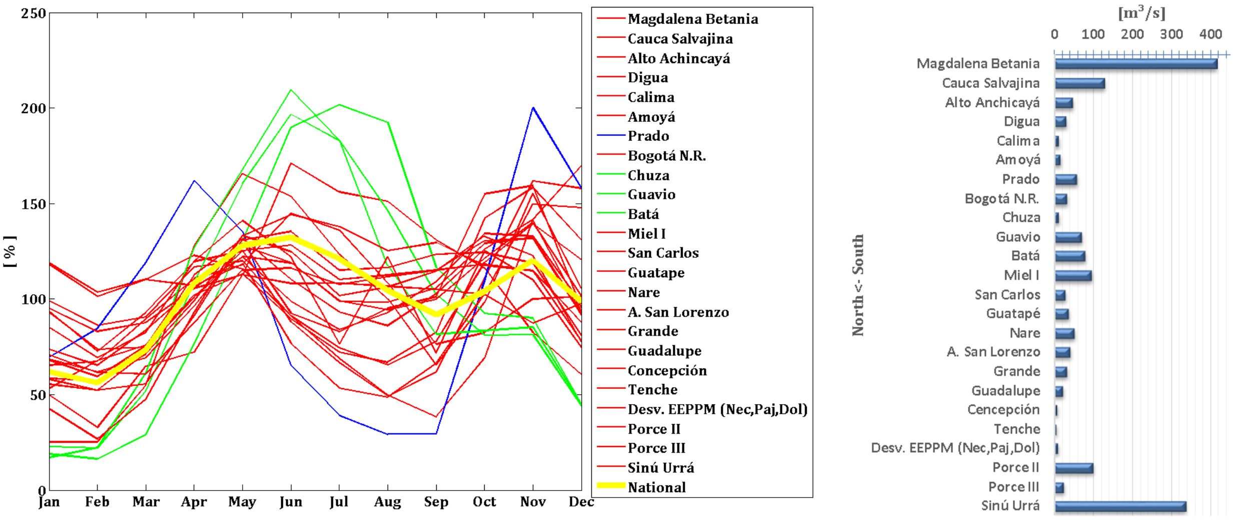

Figure 13: (Left) 3-groups-clustering executed on © Matlab showing the monthly behaviour of the mean in-flows of the 24 rivers selected plus the national aggregate (in yellow) and (Right) their mean in-flows, presented from south to north[1], from 2001 to 2014[2]

The the XM-based hydro resource indexes are presented in the Table 18along with their IAVs. The values presented here can also be graphically observed in the figures of the Appendix 11.8. The 100% value corresponds to the mean river in-flow for the specific river site between 2001-2014 [3]. The shaded values represent years with information.

		Mean in-flow [m³/s]	XM-based hydro resource index														IAV
		100%	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
North <- South	Magdalena Betania	414,6	83%	92%	79%	90%	98%	112%	112%	119%	99%	85%	127%	105%	92%	108%	13,8%
	Cauca Salvajina	127,4	78%	74%	76%	89%	105%	111%	116%	147%	91%	102%	140%	89%	82%	101%	21,8%
	Alto Anchicayá	46,1	97%	86%	107%	94%	102%	102%	111%	107%	88%	107%	110%	89%	105%	95%	8,2%
	Digua	28,9	92%	104%	105%	95%	96%	99%	120%	101%	91%	80%	106%	95%	108%	110%	9,4%
	Calima	11,7	73%	61%	88%	102%	104%	132%	126%	140%	84%	117%	117%	83%	88%	87%	22,7%
	Amoyá	15,3														100%	0,0%
	Prado	57,1	64%	71%	76%	80%	92%	109%	87%	146%	93%	112%	178%	80%	100%	112%	29,7%
	Bogotá N.R.	30,9	45%	86%	70%	91%	82%	118%	69%	117%	54%	131%	231%	120%	89%	97%	43,7%
	Chuza	10,2	100%	113%	102%	95%	91%	106%	102%	91%	87%	97%	94%	115%	101%	104%	7,8%
	Guavio	68,6	101%	116%	93%	125%	97%	104%	90%	96%	84%	79%	100%	109%	94%	112%	12,1%
	Batá	78,1	90%	107%	95%	122%	97%	118%	95%	98%	75%	82%	127%	121%	80%	93%	16,0%
	Miel I	94,5			76%	83%	112%	105%	109%	122%	108%	111%	109%	85%	80%		15,0%
	San Carlos	27,5	65%	65%	72%	91%	96%	108%	133%	108%	82%	95%	131%	107%	125%	124%	22,6%
	Guatapé	36,3	82%	77%	90%	94%	91%	102%	111%	117%	101%	108%	132%	105%	100%	92%	13,7%
	Nare	51,1	71%	70%	75%	97%	95%	100%	115%	144%	90%	117%	157%	99%	93%	77%	25,1%
	A. San Lorenzo	40,6	88%	70%	95%	90%	81%	94%	94%	135%	115%	118%	125%	106%	95%	94%	17,2%
	Grande	32,7	88%	72%	81%	84%	81%	106%	119%	136%	96%	130%	146%	99%	82%	80%	22,8%
	Guadalupe	22,1	103%	75%	100%	91%	88%	104%	126%	107%	94%	119%	112%	97%	92%	92%	12,7%
	Cencepción	6,8	91%	72%	86%	98%	93%	115%	120%	115%	92%	110%	131%	95%	90%	91%	15,5%
	Tenche	4,5	106%	71%	95%	86%	87%	110%	120%	112%	87%	117%	127%	106%	88%	89%	15,6%
	Desv. EEPPM (Nec,Paj,Dol)	8,0	137%	102%	113%	104%	100%	104%	94%	85%	108%	101%	75%	98%	89%	89%	14,2%
	Porce II	98,3		74%	89%	101%	93%	105%	115%	129%	95%	119%	118%	97%	85%	79%	16,0%
	Porce III	23,4											167%	94%	73%	67%	39,9%
	Sinú Urrá	334,7		97%	106%	85%	100%	100%	116%	104%	101%	108%	104%	93%	102%	85%	8,3%
	NATIONAL	1.550,8		88%	88%	92%	96%	106%	109%	117%	94%	99%	124%	99%	93%	96%	10,5%

Table 18: XM-based hydro resource indexes with their IAVs of the 24 river and the national group

[1] Depending on their locations within the country
[2] If less data, the mean was assessed with the available data
[3] If the river had less data, the reference period is period with data. For example, for the river Miel I, the reference period is 2003 to 2013 and its 100% values is calculated based on information of these years

5.2 Meteorological complementarities

In this subsection, the intra-annual and inter-annual meteorological complementarities are presented in matrixes organized from south to north depending of the location of the sites within the country[1]. It is important to point out that, from here onwards, the name of the large hydro power plants are used along with their single (or multiple) river(s) as shown previously in the Table 17. For example, the name Betania represents the river Magdalena Betania. However, the name San Carlos, represents the sum of the rivers San Carlos, Guatapé, Nare and A. San Lorenzo.

For the intra-annual analysis, as described in the section 4.7, there are 14 correlation coefficients between each wind site “W” and each river “R” (years 2001 and 2014), based on the 12 months of each year. The value for each pair exhibited in the tables below is the average of these 14 coefficients. On the same way, for the pairs of a solar site “S” and a river “R”.

For the inter-annual analyses, there is only one correlation coefficient between a pair “W-R” as there are only 14 values (14 years) for each site[2]. Similarly,” for the pairs “S-R” and, consequently. These unique inter-annual correlation coefficients are presented below.

In the following tables, and as described in the section 3.3, the reddest values signalize values with the most negative correlation coefficients. These represents a high inverse behaviour between a pair and thus, the pairs with the highest complementarity. These are the pairs of interest for this study. Oppositely, the greenest values signalize values with the most positive correlation´s coefficients, representing the pairs with the highest dependent pairs. Moreover, the closer the values approach to zero, the more independent the behaviour of the pairs are.

5.2.1 Wind speeds and river(s) in-flows

The mean intra-annual correlation coefficients between each pair “W-R” on a monthly basis are presented in Table 19. For a better understanding of the significance of the values in the table, three plots are presented in the Figure 14. On the right, for the national group of rivers, it can be observed why the wind site Arauca presents a large negative mean correlation´s coefficient of -0,69 as its monthly behaviour of the wind speeds is highly inverse to the river in-flows along the year. Its medium positive coefficient of +0,37 with the wind site Pacífico Sur relates to its medium dependence. For the whole matrix of rivers of the hydro power plants and the wind sites, the extreme negative (complementary) and positive (dependent) pairs are also shown in Figure 14. Between the river flowing through the hydro power plant URRÁ and the wind site CÓRDOBA, there is a large mean correlation´s coefficient of -0,81 reflecting a high complementarity between the sites. For the pair CHIVOR and TOLIMA, there is a large coefficient +0,72, presenting a high dependence between the sites.

[1] If there was not data available, the NaN (Not a Number) value is displayed in white
[2] As there are rivers with less data, the calculations were done with the available data. If there was too few annual values, the coefficients are not representative enough, as mentioned in the footnotes of the tables

Wind speeds @50m (North <- South)	River(s) in-flows of hydro power plants (South -> North)																						
	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Nariño	NaN	0,36	-0,62	-0,53	-0,58	0,86	-0,67	0,28	0,64	0,72	-0,74	NaN	-0,10	-0,07	-0,14	0,14	-0,08	0,35	0,01	0,20	NaN	NaN	0,51	0,28
Pacífico Sur	NaN	0,20	-0,39	-0,09	-0,23	0,75	-0,37	0,36	0,46	0,61	-0,33	NaN	0,25	0,24	0,20	0,35	0,25	0,50	0,33	0,36	NaN	NaN	0,61	0,37
Buenaventura Sur	NaN	0,24	-0,53	-0,37	-0,43	0,84	-0,62	0,28	0,54	0,62	-0,58	NaN	0,02	0,04	0,01	0,22	0,03	0,39	0,10	0,30	NaN	NaN	0,53	0,26
Tolima	NaN	0,34	-0,64	-0,48	-0,53	0,83	-0,63	0,31	0,65	0,72	-0,70	NaN	0,01	0,04	-0,04	0,24	-0,01	0,41	0,08	0,24	NaN	NaN	0,57	0,31
Cundinamarca	NaN	0,25	-0,64	-0,66	-0,66	0,80	-0,77	0,12	0,50	0,57	-0,76	NaN	-0,32	-0,28	-0,33	-0,07	-0,29	0,12	-0,20	0,08	NaN	NaN	0,29	0,08
Casanare	NaN	-0,41	0,21	-0,10	-0,03	-0,72	-0,12	-0,55	-0,59	-0,53	0,08	NaN	-0,55	-0,55	-0,50	-0,59	-0,47	-0,59	-0,53	-0,56	NaN	NaN	-0,61	-0,59
Boyacá	NaN	0,28	-0,65	-0,66	-0,67	0,86	-0,75	0,17	0,55	0,62	-0,78	NaN	-0,26	-0,23	-0,28	-0,02	-0,24	0,17	-0,16	0,15	NaN	NaN	0,35	0,13
Arauca	NaN	-0,47	0,26	-0,10	0,00	-0,83	-0,04	-0,64	-0,70	-0,66	0,16	NaN	-0,58	-0,59	-0,54	-0,65	-0,52	-0,69	-0,61	-0,61	NaN	NaN	-0,76	-0,69
Norte de Santander	NaN	0,18	-0,29	-0,65	-0,51	0,59	-0,63	-0,08	0,22	0,23	-0,52	NaN	-0,60	-0,56	-0,54	-0,41	-0,50	-0,27	-0,48	-0,20	NaN	NaN	-0,10	-0,15
Córdoba	NaN	-0,44	0,33	0,02	0,12	-0,85	0,21	-0,55	-0,70	-0,77	0,35	NaN	-0,45	-0,47	-0,42	-0,58	-0,45	-0,72	-0,53	-0,53	NaN	NaN	-0,81	-0,63
Atlántico	NaN	-0,27	0,45	-0,05	0,13	-0,64	0,19	-0,46	-0,59	-0,68	0,33	NaN	-0,58	-0,59	-0,51	-0,69	-0,51	-0,79	-0,62	-0,69	NaN	NaN	-0,80	-0,56
Guajira	NaN	0,13	0,23	-0,34	-0,11	-0,04	-0,15	-0,17	-0,09	-0,19	-0,04	NaN	-0,63	-0,60	-0,54	-0,58	-0,51	-0,57	-0,56	-0,50	NaN	NaN	-0,48	-0,27
San Andrés	NaN	-0,02	0,48	-0,02	0,15	-0,17	0,15	-0,18	-0,33	-0,37	0,34	NaN	-0,50	-0,50	-0,40	-0,60	-0,36	-0,61	-0,45	-0,58	NaN	NaN	-0,52	-0,27

Table 19: Intra-annual complementarity: Mean of correlation coefficient between monthly wind speeds @ 50m of selected wind sites and monthly river(s) in-flows of the selected hydro power plants for the years 2001 to 2014[1]

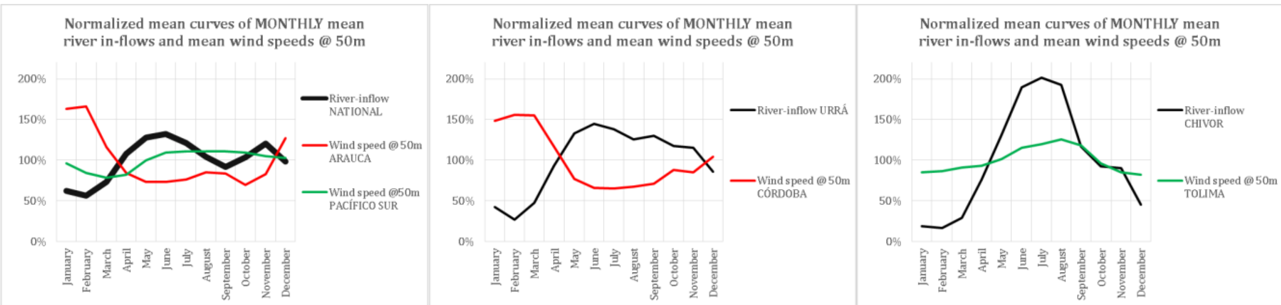

Figure 14: Normalized mean curves of monthly river in-flows and wind speeds @ 50m for different rivers and wind sites illustrating the most intra-annual complementarity (red) and the most dependent (green) site for a given river (black)

The inter-annual correlation coefficient between annual series for each pair "W-R" are presented in the Table 20. Three plots are displayed in the Figure 15 exemplifying the meaning of the obtained values. For the national group of rivers, the wind site TOLIMA gets a large correlation´s coefficient of -0,74, due to the high inverse annual behaviour of its solar insolation compared to the in-flows of the national group between 2002 and 2014. In the same figure, the extreme negative (complementary) is obtained between the river in PLAYAS and the wind site CUNDINAMARCA with a large correlation´s coefficient of -0,88. Furthermore, and contrary to the just mentioned pair, the river in GUAVIO and the wind site NARIÑO present a large positive coefficient of +0,6. This due to its large dependence through the 14 years.

[1] There are only few values for Amoyá (12 of the 168 months) and thus, they are not representative enough and are displayed in white

Wind speeds @50m (North <- South)	River(s) in-flows of hydro power plants (South -> North)																						
	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Nariño	NaN	-0,36	-0,54	-0,21	-0,41	NaN	-0,67	-0,49	0,63	0,27	-0,47	NaN	-0,79	-0,80	-0,73	-0,80	-0,76	-0,44	-0,67	-0,76	NaN	NaN	-0,45	-0,55
Pacífico Sur	NaN	-0,48	-0,40	0,30	-0,27	NaN	-0,40	-0,62	-0,31	-0,71	-0,16	NaN	-0,44	-0,50	-0,50	-0,44	-0,44	-0,06	-0,41	-0,69	NaN	NaN	0,22	-0,46
Buenaventura Sur	NaN	-0,38	-0,39	-0,03	-0,33	NaN	-0,55	-0,84	-0,14	-0,71	-0,02	NaN	-0,50	-0,55	-0,58	-0,42	-0,52	-0,17	-0,44	-0,91	NaN	NaN	-0,03	-0,50
Tolima	NaN	-0,51	-0,70	-0,32	-0,52	NaN	-0,79	-0,62	0,43	0,05	-0,54	NaN	-0,84	-0,86	-0,84	-0,78	-0,84	-0,46	-0,76	-0,80	NaN	NaN	-0,41	-0,74
Cundinamarca	NaN	-0,37	-0,64	-0,36	-0,62	NaN	-0,74	-0,70	0,53	-0,04	-0,41	NaN	-0,87	-0,88	-0,85	-0,80	-0,84	-0,57	-0,82	-0,89	NaN	NaN	-0,47	-0,67
Casanare	NaN	-0,09	-0,20	0,11	-0,13	NaN	-0,43	-0,28	0,59	0,43	-0,26	NaN	-0,42	-0,43	-0,27	-0,68	-0,46	-0,34	-0,35	0,60	NaN	NaN	-0,18	-0,24
Boyacá	NaN	-0,33	-0,59	-0,38	-0,57	NaN	-0,73	-0,71	0,52	-0,04	-0,31	NaN	-0,84	-0,86	-0,82	-0,79	-0,82	-0,57	-0,78	-0,88	NaN	NaN	-0,46	-0,64
Arauca	NaN	0,16	-0,04	0,12	-0,04	NaN	-0,30	-0,39	0,58	0,25	-0,15	NaN	-0,28	-0,33	-0,23	-0,45	-0,44	-0,42	-0,35	-1,00	NaN	NaN	-0,29	-0,15
Norte de Santander	NaN	-0,33	-0,61	-0,38	-0,63	NaN	-0,66	-0,67	0,45	-0,15	-0,38	NaN	-0,77	-0,77	-0,77	-0,64	-0,72	-0,54	-0,73	-0,98	NaN	NaN	-0,39	-0,60
Córdoba	NaN	-0,41	-0,05	-0,29	0,11	NaN	-0,20	-0,29	-0,06	-0,14	0,33	NaN	-0,20	-0,08	-0,01	-0,08	0,01	0,02	0,17	0,70	NaN	NaN	0,10	-0,17
Atlántico	NaN	-0,13	-0,36	-0,39	-0,40	NaN	-0,48	-0,58	0,49	-0,04	-0,14	NaN	-0,52	-0,50	-0,49	-0,39	-0,50	-0,46	-0,44	-0,98	NaN	NaN	-0,39	-0,37
Guajira	NaN	-0,29	-0,59	-0,33	-0,66	NaN	-0,52	-0,57	0,45	-0,18	-0,54	NaN	-0,67	-0,68	-0,73	-0,48	-0,68	-0,53	-0,72	-0,95	NaN	NaN	-0,48	-0,56
San Andrés	NaN	-0,27	-0,53	-0,66	-0,63	NaN	-0,50	-0,47	0,53	-0,05	-0,30	NaN	-0,60	-0,57	-0,62	-0,35	-0,55	-0,50	-0,56	-0,77	NaN	NaN	-0,63	-0,51

Table 20: Inter-annual complementarity: Correlation coefficient between annual wind speeds @ 50m of selected wind sites and annual river(s) in-flows of the selected hydro power plants for the years 2001 to 2014[1]

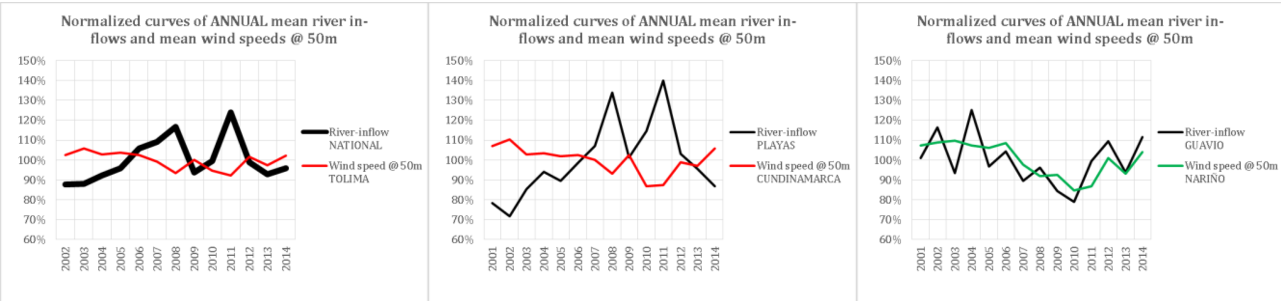

Figure 15: Normalized mean curves of annual river in-flows and wind speeds @ 50m for different rivers and wind sites illustrating the most inter-annual complementarity (red) and the most dependent (green) site for a given river (black)

5.2.2 Solar insolation and river(s) in-flows

Likewise for the wind sites, the mean intra-annual correlation coefficients between each pair "S-R" on a monthly basis are presented in Table 21. Examples of the extreme negative (complementary) and positive (dependent) pairs are displayed in the Figure 16. For the national group of rivers, the solar site ARAUCA obtains the most negative mean correlation´s coefficient, a large value of -0,73, and the solar site NARIÑO SUR gets the most positive mean coefficient, a small value of +0,05, meaning almost an independent monthly behaviour. For the whole matrix, the largest negative coefficient, -0,82, are presented between the river of the hydro power plant SALVAJINA and the solar site HUILA. The largest positive coefficient is presented between the river at CHIVOR and the solar site NARIÑO SUR, with a medium +0,53.

[1] There are only few values for Porce III (4 of the 14 years) and thus, they are not representative enough and are displayed in white

Solar insolation (North <- South)	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
	River(s) in-flows of hydro power plants (South -> North)																							
Nariño Sur	NaN	0,06	-0,82	-0,56	-0,67	0,71	-0,72	0,07	0,43	0,53	-0,77	NaN	-0,08	-0,06	-0,16	0,15	-0,18	0,26	-0,06	0,25	NaN	NaN	0,40	0,05
Cauca	NaN	0,08	-0,78	-0,65	-0,69	0,69	-0,75	0,01	0,40	0,47	-0,78	NaN	-0,20	-0,18	-0,27	0,03	-0,30	0,13	-0,19	0,09	NaN	NaN	0,29	-0,01
Huila	NaN	-0,03	-0,82	-0,56	-0,64	0,67	-0,71	0,00	0,36	0,44	-0,75	NaN	-0,08	-0,05	-0,15	0,15	-0,19	0,23	-0,08	0,20	NaN	NaN	0,37	-0,01
inamarca Occidente	NaN	0,02	-0,77	-0,70	-0,73	0,76	-0,82	-0,06	0,35	0,43	-0,81	NaN	-0,32	-0,28	-0,36	-0,06	-0,39	0,05	-0,28	0,02	NaN	NaN	0,22	-0,09
Casanare	NaN	-0,41	-0,26	-0,41	-0,39	-0,36	-0,44	-0,49	-0,37	-0,25	-0,34	NaN	-0,62	-0,61	-0,62	-0,55	-0,60	-0,51	-0,60	-0,54	NaN	NaN	-0,43	-0,60
Boyacá	NaN	-0,35	-0,73	-0,64	-0,68	0,57	-0,76	-0,36	-0,03	0,10	-0,71	NaN	-0,39	-0,38	-0,45	-0,20	-0,48	-0,14	-0,39	-0,04	NaN	NaN	0,01	-0,39
Antioquia	NaN	-0,34	0,00	-0,36	-0,23	-0,39	-0,18	-0,49	-0,44	-0,45	-0,14	NaN	-0,69	-0,70	-0,64	-0,72	-0,63	-0,72	-0,70	-0,62	NaN	NaN	-0,62	-0,62
Arauca	NaN	-0,47	0,00	-0,33	-0,24	-0,78	-0,24	-0,64	-0,59	-0,52	-0,09	NaN	-0,66	-0,65	-0,64	-0,65	-0,64	-0,68	-0,69	-0,63	NaN	NaN	-0,71	-0,73
Norte de Santander	NaN	0,00	-0,69	-0,66	-0,70	0,61	-0,72	-0,09	0,28	0,38	-0,77	NaN	-0,30	-0,28	-0,34	-0,09	-0,37	0,02	-0,29	-0,02	NaN	NaN	0,19	-0,11
Bolivar	NaN	-0,19	0,25	-0,28	-0,12	-0,44	-0,09	-0,42	-0,44	-0,45	0,05	NaN	-0,69	-0,68	-0,61	-0,71	-0,56	-0,72	-0,64	-0,64	NaN	NaN	-0,72	-0,53
Cesar	NaN	-0,14	0,15	-0,39	-0,22	-0,31	-0,19	-0,42	-0,36	-0,37	-0,08	NaN	-0,72	-0,71	-0,65	-0,71	-0,61	-0,70	-0,69	-0,62	NaN	NaN	-0,67	-0,52
Atlántico	NaN	-0,15	0,39	-0,12	0,09	-0,54	0,17	-0,36	-0,43	-0,56	0,20	NaN	-0,55	-0,55	-0,48	-0,63	-0,46	-0,71	-0,56	-0,53	NaN	NaN	-0,73	-0,46
Guajira	NaN	-0,05	0,25	-0,26	-0,04	-0,42	0,03	-0,29	-0,25	-0,40	0,03	NaN	-0,55	-0,53	-0,48	-0,55	-0,46	-0,61	-0,55	-0,42	NaN	NaN	-0,60	-0,38
San Andrés	NaN	-0,17	0,37	0,02	0,20	-0,72	0,32	-0,29	-0,39	-0,58	0,25	NaN	-0,29	-0,29	-0,25	-0,38	-0,29	-0,54	-0,38	-0,36	NaN	NaN	-0,62	-0,38

Table 21: Intra-annual complementarity: Mean of correlation coefficients between monthly solar surface insolations of selected solar sites and monthly river(s) in-flows of the selected hydro power plants for the years 2001 to 2014[1]

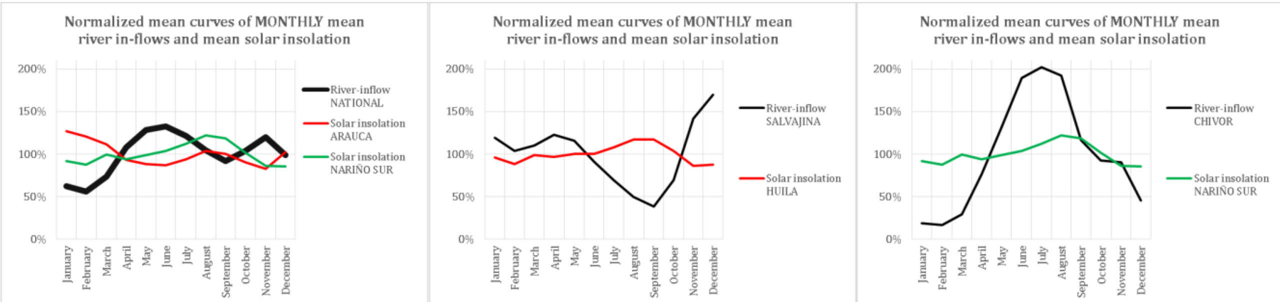

Figure 16: Normalized mean curves of monthly river in-flows and solar insolations for different rivers and solar sites illustrating the most intra-annual complementarity (red) and the most dependent (green) site for a given river (black)

The inter-annual correlation coefficients between annual series for each pair "S-R" are presented in the Table 22. Three plots are displayed in the Figure 17 showing the meaning of the obtained values. For the national group of rivers, the most complementarity solar site is NARIÑO SUR with a large coefficient of -0,74. The most dependent site is SAN ANDRÉS with a medium coefficient of +0,36. For the full matrix, the extremes are found between the river in GUATAPÉ and the solar site NARIÑO SUR with a large negative coefficient of -0,90 and between the river in GUAVIO and the solar site BOLIVAR with a large positive coefficient of +0,67.

[1] There are only few values for Amoyá (12 of the 168 months) and thus, they are not representative enough and are displayed in white

Solar insolation (North <- South)	River(s) in-flows of hydro power plants (South -> North)																							
	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Nariño Sur	NaN	-0,50	-0,74	-0,13	-0,66	NaN	-0,72	-0,72	0,33	-0,26	-0,68	NaN	-0,82	-0,87	-0,90	-0,74	-0,87	-0,48	-0,87	-0,96	NaN	NaN	-0,37	-0,74
Cauca	NaN	-0,42	-0,59	-0,14	-0,52	NaN	-0,74	-0,72	0,39	-0,08	-0,39	NaN	-0,84	-0,85	-0,81	-0,79	-0,76	-0,37	-0,73	-0,90	NaN	NaN	-0,25	-0,61
Huila	NaN	-0,52	-0,65	-0,11	-0,47	NaN	-0,79	-0,82	0,16	-0,30	-0,34	NaN	-0,85	-0,87	-0,86	-0,78	-0,78	-0,33	-0,72	-0,95	NaN	NaN	-0,11	-0,69
inamarca Occidente	NaN	-0,42	-0,49	-0,19	-0,38	NaN	-0,72	-0,68	0,39	0,03	-0,21	NaN	-0,80	-0,76	-0,69	-0,75	-0,66	-0,34	-0,56	-0,82	NaN	NaN	-0,16	-0,53
Casanare	NaN	-0,23	-0,42	0,14	-0,41	NaN	-0,53	-0,47	0,42	0,04	-0,46	NaN	-0,63	-0,67	-0,64	-0,65	-0,64	-0,39	-0,63	-0,82	NaN	NaN	-0,20	-0,44
Boyacá	NaN	-0,50	-0,61	-0,27	-0,57	NaN	-0,80	-0,78	0,20	-0,22	-0,22	NaN	-0,81	-0,77	-0,73	-0,68	-0,63	-0,31	-0,60	-0,90	NaN	NaN	-0,01	-0,61
Antioquia	NaN	-0,22	-0,29	-0,08	-0,19	NaN	-0,55	-0,50	0,52	0,24	-0,11	NaN	-0,62	-0,60	-0,48	-0,68	-0,51	-0,28	-0,38	-0,82	NaN	NaN	-0,16	-0,30
Arauca	NaN	0,35	0,16	0,31	0,04	NaN	0,06	-0,03	0,34	0,11	-0,26	NaN	0,13	0,03	0,01	0,02	-0,15	-0,28	-0,22	-0,88	NaN	NaN	-0,32	0,00
Norte de Santander	NaN	-0,25	-0,40	-0,27	-0,52	NaN	-0,56	-0,61	0,13	-0,27	-0,05	NaN	-0,55	-0,52	-0,54	-0,35	-0,40	-0,22	-0,42	-0,82	NaN	NaN	-0,01	-0,32
Bolivar	NaN	0,30	0,05	-0,11	-0,13	NaN	-0,15	-0,19	0,67	0,36	0,19	NaN	-0,30	-0,32	-0,24	-0,39	-0,31	-0,42	-0,31	-0,26	NaN	NaN	-0,40	-0,02
Cesar	NaN	0,25	-0,06	-0,13	-0,28	NaN	-0,19	-0,33	0,58	0,08	0,06	NaN	-0,34	-0,39	-0,36	-0,37	-0,46	-0,56	-0,47	-0,75	NaN	NaN	-0,48	-0,15
Atlántico	NaN	0,33	0,07	-0,22	-0,23	NaN	0,08	-0,16	0,37	-0,10	0,28	NaN	-0,11	-0,14	-0,17	-0,02	-0,21	-0,45	-0,28	-0,71	NaN	NaN	-0,45	0,01
Guajira	NaN	0,17	-0,16	-0,15	-0,36	NaN	-0,14	-0,36	0,43	-0,12	-0,14	NaN	-0,31	-0,37	-0,41	-0,25	-0,50	-0,57	-0,53	-0,88	NaN	NaN	-0,51	-0,21
San Andrés	NaN	0,45	0,18	-0,17	-0,09	NaN	0,35	0,38	0,40	0,33	-0,08	NaN	0,30	0,27	0,21	0,32	0,18	-0,06	0,10	0,92	NaN	NaN	-0,46	0,36

Table 22: Inter-annual complementarity: Correlation coefficient between annual solar surface insolations of selected solar sites and annual river(s) in-flows of the selected hydro power plants for the years 2001 to 2014[1]

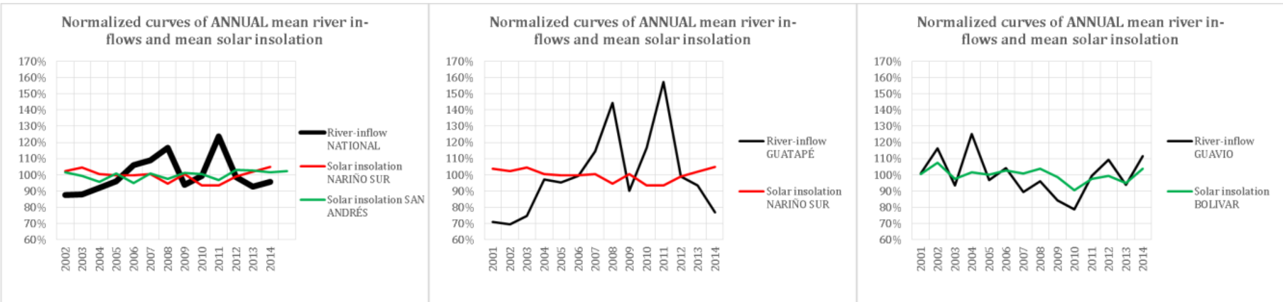

Figure 17: Normalized mean curves of annual river in-flows and solar insolations for different rivers and solar sites illustrating the most inter-annual complementarity (red) and the most dependent (green) site for a given river (black)

[1] There are only few values for Porce III (4 of the 14 years) and thus, they are not representative enough and are displayed in white

6 Energy results

In this section, the magnitude of the energy calculations for simulated wind, solar and hydro power plants are presented along with their intra-annual and inter-annual correlation coefficients. It is indispensable to mention again that the importance of this study resides in the monthly and annual behaviour of the wind, solar and hydro resources as well as the complementarities of the wind/solar resource to the hydro resources in Colombia and not in their magnitudes. Due to the intensification uncertainties from the meteorological resources, especially for the wind power[1], these are first ESTIMATES and are likely to be strongly underestimated. Therefore, they should be addressed carefully and should not be used for commercial purposes without the corresponding future works proposed later on.

6.1 Energy generations and annual energy indexes

Following the procedures in the subsection 4.6, meteorological resources were translated into energy generation. As a summary, the inputs for the energy calculations are presented in the Table 23:

	Inputs for calculations
Wind energy (99 MW at each wind site)	**From Stream 3 of MERRA (2001-2014):** - Hourly wind speed @ 50m - Mean monthly roughness lengths - Mean monthly surface air densities **From the German wind power developer Notus energy:** - Power curve turbine VESTAS V126 3,3MW - Estimated losses for a 30 x 3,3MW wind park -
PV solar energy (50MWp at each solar site)	**From Stream 3 of MERRA (2001-2014):** - Hourly solar surface irradiance - Hourly temperature at 2m above surface **From the Mulcué-Nieto and Mora-Lopez paper [63]:** - Best Performance Ratio (PR) for solar systems in Colombia **From solar modules manufacturer Yingli Solar:** - Temperature coefficient[2] of polycrystalline solar cell YGE 60 and monocrystalline Panda 60 - Nominal Operating Cell Temperature (NOCT) of same cells -
Hydroelectric energy (different rated capacities[3])	**From Colombian power system operator XM (2001-2014):** - Monthly river in-flows - Rated capacities of large hydro power plants - Conversion factors of large hydro power plants

Table 23: Inputs for assessing the energy production of the wind-, solar and hydro power plants simulated

[1] Wind power is proportional to the wind speed to the power of 3 [50]
[2] Both solar cells have the same temperature coefficients and NOCT
[3] Please refer to Table 17

The Monthly Energy Production (MEP) and the Annual Energy Production (AEP) were calculated for each power plant (wind, solar and hydro) between 2001 and 2014. The displayed mean AEP, the 100%, is the average of these 14 AEPs assessed. Besides this, as described in the subsection 4.8, the MERRA-based energy indexes for wind and solar power plants and the XM-based energy index for hydro power plants were assessed respectively. The IAVs follow the definition of the subsection 4.8. Similarly to the resource indexes shown previously, the bluest values refer to the highest indexes, consequently the years with highest energy production; the reddest values the lowest, representing years with the lowest energy productions. Both, the figures with the AEPs and the tables with the corresponding energy indexes are organized based on the geographical location of the sites from south (top) to north (bottom).

Wind energy

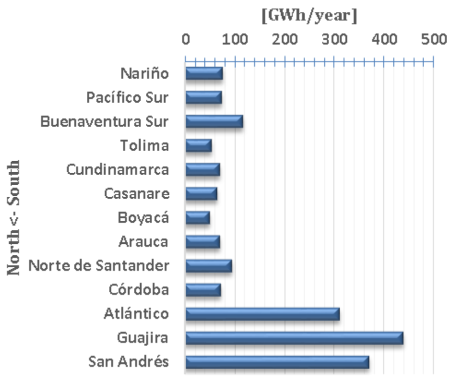

Figure 18: Mean AEP of a 99MW (30 x V126 3,3MW) wind park at each of the 13 selected wind sites between 2001 and 2014

		AEP [GWh/year]	MERRA-based wind energy index for a 99MW wind park at each wind site														IAV
		100%	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
North <- South	Nariño	74,0	115%	120%	123%	116%	122%	131%	88%	78%	77%	59%	70%	103%	82%	117%	22,7%
	Pacífico Sur	72,5	104%	99%	110%	97%	104%	91%	109%	88%	98%	100%	91%	88%	107%	112%	7,7%
	Buenaventura Sur	113,6	110%	102%	102%	99%	101%	95%	107%	95%	106%	91%	84%	94%	103%	113%	7,6%
	Tolima	52,0	103%	107%	118%	113%	119%	115%	93%	80%	96%	79%	78%	103%	89%	107%	14,1%
	Cundinamarca	67,7	114%	128%	102%	109%	103%	111%	94%	85%	105%	66%	72%	100%	91%	120%	16,7%
	Casanare	62,2	106%	118%	103%	118%	103%	94%	115%	108%	84%	70%	92%	96%	98%	94%	13,0%
	Boyacá	46,8	106%	124%	97%	111%	110%	114%	90%	86%	108%	64%	76%	101%	92%	120%	16,5%
	Arauca	68,1	98%	122%	108%	116%	97%	95%	110%	118%	95%	60%	80%	96%	100%	105%	15,4%
	Norte de Santander	91,7	123%	140%	98%	107%	83%	104%	100%	91%	109%	68%	70%	94%	99%	114%	18,6%
	Córdoba	70,7	108%	113%	106%	134%	115%	103%	97%	104%	114%	103%	76%	77%	81%	70%	17,3%
	Atlántico	309,9	107%	122%	92%	114%	89%	100%	100%	107%	113%	78%	84%	94%	98%	103%	11,7%
	Guajira	437,2	115%	120%	103%	102%	81%	100%	94%	95%	112%	72%	79%	98%	109%	119%	14,3%
	San Andrés	369,1	111%	119%	93%	110%	85%	97%	92%	96%	112%	87%	86%	103%	96%	113%	10,9%

Table 24: MERRA-based wind energy indexes and their IAVs for a 99MW (30 x V126 3,3MW) wind park at each of the 13 selected wind sites

PV solar energy

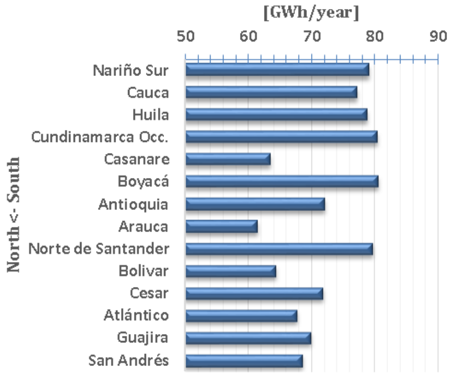

Figure 19: Mean AEP of a 50MW solar park at each of the 14 selected solar sites between 2001 and 2014

		AEP [GWh/year]	MERRA-based solar energy index for a 50MW solar park at each site														IAV
		100%	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
North <- South	Nariño Sur	78,9	104%	102%	104%	101%	100%	100%	101%	95%	101%	94%	94%	99%	102%	104%	3,3%
	Cauca	77,0	107%	105%	105%	101%	102%	102%	102%	96%	99%	91%	93%	98%	98%	102%	4,3%
	Huila	78,6	104%	103%	105%	100%	102%	102%	102%	96%	101%	95%	92%	97%	99%	102%	3,5%
	Cundinamarca Occ.	80,3	107%	107%	105%	103%	104%	103%	102%	98%	99%	91%	90%	97%	94%	99%	5,3%
	Casanare	63,3	101%	104%	106%	99%	101%	100%	102%	99%	96%	93%	95%	100%	99%	104%	3,4%
	Boyacá	80,5	106%	106%	103%	100%	101%	99%	102%	98%	102%	95%	94%	99%	97%	99%	3,5%
	Antioquia	71,9	106%	108%	103%	105%	104%	105%	102%	101%	96%	90%	93%	96%	95%	97%	5,3%
	Arauca	61,4	96%	100%	100%	100%	99%	98%	102%	104%	97%	95%	98%	103%	102%	105%	2,9%
	Norte de Santander	79,6	104%	103%	100%	98%	99%	99%	101%	101%	100%	97%	97%	101%	100%	100%	1,9%
	Bolivar	64,3	100%	107%	97%	101%	100%	103%	101%	104%	99%	92%	98%	100%	96%	103%	3,6%
	Cesar	71,7	100%	104%	97%	100%	100%	101%	100%	103%	101%	93%	97%	100%	99%	104%	2,8%
	Atlántico	67,6	101%	104%	94%	98%	97%	100%	98%	106%	103%	93%	98%	99%	101%	107%	3,9%
	Guajira	69,9	101%	102%	98%	100%	98%	101%	99%	102%	103%	92%	97%	100%	103%	106%	3,3%
	San Andrés	68,5	102%	99%	96%	101%	95%	101%	98%	101%	101%	97%	103%	103%	102%	102%	2,4%

Table 25: MERRA-based solar energy indexes and their IAVs for a 50MW solar park at each of the 14 selected solar sites

Hydroelectric energy

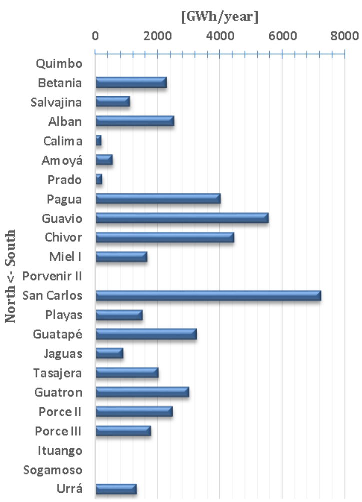

Figure 20: Mean AEP of selected hydro power plants between 2001 and 2014[1]

[1] If less data, the mean was assessed with the available data, Please consider the rated capacities presented in the Table 17

		Rated capacity [MW]	AEP [GWh/year]	XM-based hydroelectric energy index														IAV
			100%	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
North <- South	Quimbo	400																
	Betania	540	2.265	83%	93%	79%	91%	98%	112%	109%	119%	99%	85%	127%	105%	92%	108%	14%
	Salvajina	285	1.100	78%	74%	77%	90%	106%	112%	115%	148%	91%	99%	136%	90%	82%	101%	21%
	Alban	429	2.523	96%	95%	106%	96%	100%	102%	112%	107%	90%	93%	104%	93%	104%	101%	6%
	Calima	132	192	73%	61%	88%	102%	104%	132%	127%	140%	84%	117%	117%	83%	88%	86%	23%
	Amoyá	80	549														100%	
	Prado	46	218	71%	78%	86%	84%	96%	116%	98%	136%	99%	105%	130%	88%	101%	113%	18%
	Pagua	600	4.006	82%	89%	101%	103%	97%	100%	97%	105%	82%	99%	122%	115%	103%	105%	11%
	Guavio	1.200	5.543	104%	109%	99%	111%	102%	109%	91%	93%	86%	84%	105%	111%	98%	99%	9%
	Chivor	1.000	4.441	92%	96%	99%	105%	104%	112%	100%	97%	81%	87%	130%	115%	87%	93%	12%
	Miel I	396	1.657			77%	84%	112%	106%	110%	122%	108%	111%	107%	85%	80%		15%
	Porvenir II	352																
	San Carlos	1.240	7.219	80%	73%	86%	95%	92%	101%	108%	123%	101%	108%	130%	103%	104%	96%	15%
	Playas	207	1.516	90%	83%	93%	97%	93%	101%	105%	112%	111%	99%	115%	103%	101%	97%	9%
	Guatapé	560	3.234	76%	74%	79%	100%	101%	104%	114%	135%	96%	109%	134%	98%	99%	82%	18%
	Jaguas	170	894	89%	71%	96%	91%	82%	96%	95%	121%	117%	118%	125%	106%	97%	95%	15%
	Tasajera	306	2.017	97%	80%	89%	92%	87%	106%	114%	120%	104%	103%	126%	104%	90%	87%	13%
	Guatron	512	3.001	108%	80%	101%	95%	92%	107%	117%	105%	96%	109%	110%	98%	91%	92%	10%
	Porce II	405	2.471		76%	90%	99%	93%	106%	113%	123%	99%	110%	122%	98%	88%	82%	14%
	Porce III	700	1.773											133%	98%	85%	84%	20%
	Ituango	2.400																
	Sogamoso	820																
	Urrá	338	1.316		97%	106%	85%	100%	100%	116%	104%	101%	108%	104%	93%	102%	85%	8%
	NATIONAL	7.970	42.270		86%	92%	98%	96%	105%	105%	112%	93%	99%	120%	103%	96%	94%	9%

Table 26: XM–based hydroelectric energy indexes and their IAVs of selected hydro power plants[1]

6.2 Energy complementarities

Exactly as executed with the meteorological resources, the energy intra-annual and inter-annual complementarities between wind parks "WP" and the hydro power plants "HPP" as well as between the solar parks "SP" and the "HPP" were analysed and are exhibited in the following tables. Please refer to the subsection 5.2 for a better understanding of the colours and the organization.

		Hydro power plants (South -> North)																						
		Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Wind parks (North <- South)	Nariño	NaN	0,38	-0,59	-0,51	-0,56	0,68	-0,67	0,40	0,64	0,72	-0,74	NaN	-0,04	0,05	-0,07	0,17	0,03	0,36	0,08	0,21	NaN	NaN	0,53	0,41
	Pacífico Sur	NaN	0,24	-0,44	-0,16	-0,29	0,82	-0,46	0,42	0,49	0,64	-0,39	NaN	0,24	0,24	0,19	0,34	0,24	0,48	0,31	0,37	NaN	NaN	0,60	0,46
	Buenaventura Sur	NaN	0,31	-0,58	-0,44	-0,50	0,78	-0,71	0,35	0,60	0,68	-0,66	NaN	0,04	0,10	0,02	0,22	0,05	0,37	0,11	0,30	NaN	NaN	0,55	0,39
	Tolima	NaN	0,33	-0,63	-0,45	-0,52	0,74	-0,64	0,46	0,63	0,72	-0,69	NaN	0,09	0,16	0,03	0,28	0,09	0,42	0,15	0,27	NaN	NaN	0,58	0,45
	Cundinamarca	NaN	0,30	-0,62	-0,63	-0,64	0,60	-0,76	0,21	0,52	0,58	-0,77	NaN	-0,22	-0,14	-0,24	-0,02	-0,16	0,16	-0,10	0,11	NaN	NaN	0,35	0,22
	Casanare	NaN	-0,44	0,23	-0,10	0,00	-0,74	-0,06	-0,73	-0,65	-0,61	0,11	NaN	-0,58	-0,61	-0,54	-0,62	-0,52	-0,62	-0,56	-0,54	NaN	NaN	-0,63	-0,71
	Boyacá	NaN	0,33	-0,63	-0,60	-0,63	0,66	-0,74	0,28	0,57	0,63	-0,77	NaN	-0,16	-0,08	-0,17	0,05	-0,10	0,22	-0,05	0,18	NaN	NaN	0,41	0,28
	Arauca	NaN	-0,49	0,20	-0,17	-0,05	-0,91	-0,03	-0,80	-0,72	-0,69	0,13	NaN	-0,63	-0,65	-0,60	-0,68	-0,59	-0,72	-0,65	-0,62	NaN	NaN	-0,77	-0,81
	Norte de Santander	NaN	0,19	-0,28	-0,61	-0,49	0,34	-0,60	-0,14	0,18	0,18	-0,53	NaN	-0,54	-0,46	-0,48	-0,38	-0,42	-0,25	-0,42	-0,18	NaN	NaN	-0,07	-0,15
	Córdoba	NaN	-0,43	0,27	-0,05	0,05	-0,82	0,17	-0,66	-0,68	-0,76	0,28	NaN	-0,51	-0,54	-0,48	-0,60	-0,53	-0,73	-0,60	-0,54	NaN	NaN	-0,78	-0,72
	Atlántico	NaN	-0,28	0,46	-0,06	0,15	-0,79	0,23	-0,63	-0,64	-0,74	0,33	NaN	-0,62	-0,61	-0,55	-0,71	-0,56	-0,79	-0,64	-0,69	NaN	NaN	-0,79	-0,72
	Guajira	NaN	0,15	0,23	-0,34	-0,10	-0,28	-0,11	-0,33	-0,12	-0,23	-0,05	NaN	-0,62	-0,55	-0,54	-0,56	-0,50	-0,54	-0,55	-0,49	NaN	NaN	-0,44	-0,39
	San Andrés	NaN	0,00	0,47	-0,03	0,16	-0,34	0,16	-0,37	-0,37	-0,41	0,34	NaN	-0,51	-0,50	-0,42	-0,60	-0,41	-0,58	-0,46	-0,58	NaN	NaN	-0,48	-0,45

Table 27: Intra-annual complementarity: Mean of correlation coefficients between monthly energy productions of wind parks and monthly energy production of the selected hydro power plants for the years 2001 to 2014[2]

[1] For the hydroelectric energy, as some rivers have less data, there are gaps (shaded cells) for these years. Same for the four recent/future projects

[2] Values for Amoyá are based on very few values (data for 12 of the 168 months) and thus, are not representative enough

		Hydro power plants (South -> North)																							
		Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Wind parks (North <- South)	Nariño	NaN	-0,26	-0,42	0,00	-0,35	NaN	-0,48	-0,21	0,67	0,15	-0,39	NaN	-0,73	-0,68	-0,65	-0,80	-0,62	-0,40	-0,60	-0,71	NaN	NaN	-0,50	-0,45
	Pacífico Sur	NaN	-0,52	-0,47	0,28	-0,35	NaN	-0,39	-0,37	-0,33	-0,52	-0,30	NaN	-0,47	-0,47	-0,55	-0,46	-0,56	-0,14	-0,53	-0,71	NaN	NaN	0,10	-0,56
	Buenaventura Sur	NaN	-0,40	-0,48	0,05	-0,47	NaN	-0,48	-0,65	-0,18	-0,64	-0,17	NaN	-0,62	-0,45	-0,67	-0,56	-0,56	-0,28	-0,62	-0,91	NaN	NaN	-0,19	-0,67
	Tolima	NaN	-0,39	-0,52	-0,10	-0,38	NaN	-0,55	-0,28	0,53	0,05	-0,42	NaN	-0,74	-0,65	-0,67	-0,75	-0,68	-0,43	-0,63	-0,75	NaN	NaN	-0,46	-0,56
	Cundinamarca	NaN	-0,26	-0,54	-0,21	-0,60	NaN	-0,54	-0,50	0,47	-0,18	-0,36	NaN	-0,80	-0,63	-0,77	-0,78	-0,67	-0,58	-0,76	-0,82	NaN	NaN	-0,58	-0,65
	Casanare	NaN	-0,03	-0,10	0,36	-0,14	NaN	-0,36	-0,13	0,49	0,16	-0,22	NaN	-0,37	-0,37	-0,17	-0,63	-0,24	-0,23	-0,21	-0,68	NaN	NaN	-0,16	-0,12
	Boyacá	NaN	-0,14	-0,44	-0,23	-0,53	NaN	-0,44	-0,40	0,52	-0,09	-0,27	NaN	-0,71	-0,53	-0,67	-0,73	-0,63	-0,64	-0,71	-0,80	NaN	NaN	-0,64	-0,58
	Arauca	NaN	0,01	-0,11	0,31	-0,20	NaN	-0,22	-0,19	0,33	-0,08	-0,22	NaN	-0,37	-0,27	-0,26	-0,52	-0,31	-0,42	-0,35	-0,99	NaN	NaN	-0,28	-0,28
	Norte de Santander	NaN	-0,30	-0,56	-0,20	-0,63	NaN	-0,56	-0,60	0,32	-0,35	-0,38	NaN	-0,75	-0,58	-0,73	-0,68	-0,56	-0,51	-0,69	-0,95	NaN	NaN	-0,42	-0,65
	Córdoba	NaN	-0,46	-0,22	-0,26	0,00	NaN	-0,41	-0,59	0,01	-0,25	0,10	NaN	-0,42	-0,33	-0,16	-0,33	-0,26	-0,13	-0,03	0,07	NaN	NaN	-0,01	-0,35
	Atlántico	NaN	-0,09	-0,28	-0,19	-0,39	NaN	-0,34	-0,52	0,24	-0,31	-0,10	NaN	-0,47	-0,26	-0,39	-0,44	-0,32	-0,47	-0,39	-0,98	NaN	NaN	-0,41	-0,42
	Guajira	NaN	-0,25	-0,54	-0,16	-0,66	NaN	-0,41	-0,48	0,23	-0,41	-0,49	NaN	-0,61	-0,39	-0,70	-0,48	-0,51	-0,52	-0,69	-0,96	NaN	NaN	-0,48	-0,59
	San Andrés	NaN	-0,22	-0,50	-0,50	-0,66	NaN	-0,46	-0,46	0,29	-0,33	-0,33	NaN	-0,57	-0,38	-0,63	-0,39	-0,45	-0,54	-0,58	-0,79	NaN	NaN	-0,66	-0,54

Table 28: Inter-annual complementarity: Correlation coefficient between AEPs of wind parks and AEPs of the selected hydro power plants for the years 2001 to 2014[1]

		Hydro power plants (South -> North)																							
		Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Solar parks (North <- South)	Nariño Sur	NaN	0,12	-0,76	-0,49	-0,61	0,73	-0,72	0,30	0,51	0,58	-0,74	NaN	0,03	0,10	-0,05	0,21	-0,03	0,30	0,04	0,30	NaN	NaN	0,46	0,30
	Cauca	NaN	0,14	-0,73	-0,58	-0,63	0,66	-0,74	0,21	0,48	0,52	-0,76	NaN	-0,09	-0,02	-0,16	0,11	-0,14	0,19	-0,08	0,16	NaN	NaN	0,36	0,21
	Huila	NaN	0,08	-0,75	-0,48	-0,58	0,75	-0,70	0,26	0,47	0,53	-0,72	NaN	0,03	0,09	-0,05	0,22	-0,04	0,29	0,03	0,26	NaN	NaN	0,44	0,27
	inamarca Occidente	NaN	0,12	-0,70	-0,61	-0,65	0,71	-0,79	0,16	0,44	0,49	-0,77	NaN	-0,18	-0,10	-0,22	0,04	-0,19	0,14	-0,14	0,10	NaN	NaN	0,32	0,16
	Casanare	NaN	-0,33	-0,29	-0,41	-0,38	-0,21	-0,48	-0,45	-0,28	-0,18	-0,38	NaN	-0,58	-0,55	-0,60	-0,50	-0,53	-0,44	-0,54	-0,43	NaN	NaN	-0,31	-0,49
	Boyacá	NaN	-0,22	-0,71	-0,57	-0,63	0,67	-0,76	-0,10	0,13	0,22	-0,72	NaN	-0,26	-0,21	-0,32	-0,09	-0,30	-0,02	-0,25	0,06	NaN	NaN	0,14	-0,09
	Antioquia	NaN	-0,23	0,01	-0,33	-0,19	-0,15	-0,17	-0,45	-0,36	-0,41	-0,16	NaN	-0,64	-0,60	-0,61	-0,66	-0,56	-0,63	-0,62	-0,51	NaN	NaN	-0,49	-0,58
	Arauca	NaN	-0,44	-0,02	-0,34	-0,24	-0,71	-0,24	-0,69	-0,58	-0,52	-0,12	NaN	-0,67	-0,65	-0,66	-0,66	-0,63	-0,67	-0,68	-0,58	NaN	NaN	-0,65	-0,74
	Norte de Santander	NaN	0,10	-0,62	-0,56	-0,61	0,62	-0,71	0,14	0,38	0,45	-0,74	NaN	-0,18	-0,10	-0,22	0,00	-0,19	0,11	-0,15	0,07	NaN	NaN	0,30	0,12
	Bolivar	NaN	-0,15	0,26	-0,29	-0,10	-0,54	-0,07	-0,57	-0,46	-0,49	0,05	NaN	-0,70	-0,67	-0,62	-0,71	-0,56	-0,69	-0,63	-0,60	NaN	NaN	-0,66	-0,64
	Cesar	NaN	-0,08	0,15	-0,40	-0,21	-0,40	-0,18	-0,50	-0,35	-0,38	-0,10	NaN	-0,72	-0,67	-0,65	-0,69	-0,59	-0,66	-0,66	-0,57	NaN	NaN	-0,58	-0,59
	Atlántico	NaN	-0,13	0,41	-0,12	0,11	-0,51	0,22	-0,50	-0,45	-0,60	0,21	NaN	-0,57	-0,55	-0,50	-0,63	-0,48	-0,70	-0,57	-0,51	NaN	NaN	-0,69	-0,59
	Guajira	NaN	-0,01	0,27	-0,25	-0,02	-0,39	0,06	-0,37	-0,23	-0,40	0,02	NaN	-0,54	-0,49	-0,48	-0,53	-0,45	-0,58	-0,53	-0,39	NaN	NaN	-0,54	-0,45
	San Andrés	NaN	-0,14	0,39	0,03	0,22	-0,57	0,36	-0,34	-0,36	-0,56	0,27	NaN	-0,29	-0,28	-0,26	-0,37	-0,29	-0,52	-0,37	-0,34	NaN	NaN	-0,58	-0,43

Table 29: Intra-annual complementarity: Mean of correlation coefficients between monthly energy productions of solar parks and monthly energy production of the selected hydro power plants for the years 2001 to 2014[2]

		Hydro power plants (South -> North)																							
		Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Solar parks (North <- South)	Nariño Sur	NaN	-0,50	-0,70	0,03	-0,65	NaN	-0,64	-0,47	0,24	-0,36	-0,65	NaN	-0,78	-0,62	-0,85	-0,72	-0,72	-0,43	-0,81	-0,97	NaN	NaN	-0,36	-0,72
	Cauca	NaN	-0,42	-0,55	0,06	-0,51	NaN	-0,65	-0,59	0,35	-0,21	-0,36	NaN	-0,84	-0,69	-0,77	-0,81	-0,61	-0,31	-0,67	-0,91	NaN	NaN	-0,25	-0,64
	Huila	NaN	-0,53	-0,61	0,06	-0,46	NaN	-0,65	-0,67	0,13	-0,38	-0,30	NaN	-0,84	-0,69	-0,79	-0,79	-0,67	-0,30	-0,68	-0,95	NaN	NaN	-0,12	-0,73
	inamarca Occidente	NaN	-0,40	-0,43	0,02	-0,34	NaN	-0,62	-0,60	0,36	-0,13	-0,16	NaN	-0,80	-0,68	-0,62	-0,79	-0,54	-0,28	-0,49	-0,81	NaN	NaN	-0,17	-0,55
	Casanare	NaN	-0,22	-0,37	0,35	-0,39	NaN	-0,42	-0,19	0,36	-0,04	-0,42	NaN	-0,64	-0,60	-0,62	-0,71	-0,53	-0,33	-0,59	-0,81	NaN	NaN	-0,20	-0,45
	Boyacá	NaN	-0,50	-0,58	-0,11	-0,57	NaN	-0,75	-0,76	0,16	-0,35	-0,19	NaN	-0,84	-0,67	-0,71	-0,72	-0,52	-0,29	-0,58	-0,88	NaN	NaN	-0,03	-0,69
	Antioquia	NaN	-0,22	-0,24	0,13	-0,17	NaN	-0,47	-0,45	0,50	0,06	-0,08	NaN	-0,65	-0,59	-0,42	-0,76	-0,39	-0,22	-0,31	-0,81	NaN	NaN	-0,16	-0,32
	Arauca	NaN	0,38	0,22	0,45	0,05	NaN	0,24	0,43	0,14	0,09	-0,23	NaN	0,16	0,14	0,08	-0,07	-0,04	-0,25	-0,18	-0,86	NaN	NaN	-0,34	0,05
	Norte de Santander	NaN	-0,24	-0,36	-0,10	-0,50	NaN	-0,49	-0,59	0,14	-0,34	-0,03	NaN	-0,57	-0,42	-0,52	-0,45	-0,25	-0,19	-0,42	-0,80	NaN	NaN	-0,02	-0,41
	Bolivar	NaN	0,34	0,12	0,11	-0,11	NaN	-0,03	-0,15	0,49	0,18	0,24	NaN	-0,31	-0,24	-0,18	-0,48	-0,15	-0,35	-0,24	-0,22	NaN	NaN	-0,40	-0,10
	Cesar	NaN	0,30	0,02	0,10	-0,25	NaN	-0,01	-0,19	0,35	-0,06	0,09	NaN	-0,29	-0,17	-0,26	-0,44	-0,25	-0,48	-0,39	-0,75	NaN	NaN	-0,49	-0,21
	Atlántico	NaN	0,36	0,12	-0,07	-0,22	NaN	0,20	-0,19	0,09	-0,24	0,29	NaN	-0,07	0,06	-0,13	-0,09	-0,06	-0,40	-0,24	-0,72	NaN	NaN	-0,44	-0,10
	Guajira	NaN	0,20	-0,11	0,02	-0,35	NaN	0,02	-0,22	0,23	-0,23	-0,12	NaN	-0,24	-0,05	-0,33	-0,29	-0,27	-0,50	-0,46	-0,89	NaN	NaN	-0,51	-0,26
	San Andrés	NaN	0,47	0,19	-0,17	-0,08	NaN	0,28	0,31	0,34	0,24	-0,09	NaN	0,33	0,41	0,17	0,34	0,34	0,01	0,16	0,92	NaN	NaN	-0,45	0,42

Table 30: Inter-annual complementarity: Correlation coefficients between AEPs of solar parks and AEPs of the selected hydro power plants for the years 2001 to 2014[3]

[1] Values for Porce III are based on very few values (data for 4 of the 14 years) and thus, are not representative enough
[2] Values for Amoyá are based on very few values (data for 12 of the 168 months) and thus, are not representative enough
[3] Values for Porce III are based on very few values (data for 4 of the 14 years) and thus, are not representative enough

7 Discussion

7.1 Case studies on Reanalysis and MERRA accuracy[1]

Following, examples of international case studies dealing with Reanalysis data (including MERRA) are chronologically presented as to give a general overview of how much site-dependent the accuracies these models might be.

7.1.1 Under- and overestimation of data

Wind speeds

As shown in Figure 21, on the left, Brower [64] showed in a research note in 2006 several discrepancies between mean annual wind speeds from the Reanalysis NCEP/NCAR and observations of a rawinsonde located west to the Rocky Mountains (peaking at 4.400m above sea level), USA. It was concluded that mountains made it difficult for the model to match the observations early in the 30 years period because it was the only source of atmospheric information nearby and due to the rough surface smoothing produced by the model resolution (210km). This produced underestimation of the wind speeds. Later on, more satellite and aircraft data in the area gradually forced the model to converge more closely to the observations. On a second example, on the right of Figure 21, a flat terrain in UK obtained relatively good agreement between the model and observations made. For the following section, it is important to emphasize how, although the magnitudes are different, the curves were following similar patterns in both examples. Brower also pointed out the fact that the data assimilation system interpolates not only observations to a regular grid but also tries to reconcile observations (temperature, pressure, wind among others) with terrain and surface conditions, according to the physical laws of the atmosphere conducted by the model. As the wind is derived from the fundamental parameters of temperature and pressure, if the observed wind is not consistent with the observed pressure and temperature gradients, the model can just override observations.

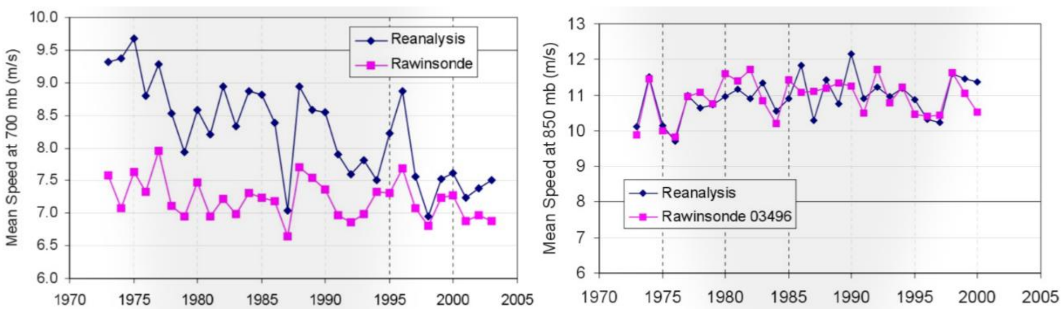

Figure 21: Mean annual wind speeds in (Left) USA at 700mb (3.500m) and (Right) Great Britain at 850m (1.500m) from NCEP/NCAR and rawinsondes. Taken from Brower [64]

[1] A special acknowledgement to Dr. Michael Brower, author of several papers referenced here, who kindly provided very interesting information about Reanalysis during the development of the present study

In 2012, Ruiz Murcia [65] ran the WRF model with the CSFR Reanalysis data for months in 2012 in the Guajira, north of Colombia, and compared the results with a 80m MET tower located in the center of the simulation . For this short period, a bias of about +2m/s (overestimation) was found in the model. In 2013, Archer and Jacobson [66] found monthly negative biases (underestimation) on MERRA wind speeds, extrapolated @ 100m, compared to 62 to 135 soundings stations from all around the globe[1] (Figure 24). The mean monthly biases were located between -0,59m/s (in February) to -0,91m/s (in May) with an average of -0,74m/s. The criteria for the mentioned sounding stations was to have a monthly-average wind speed larger than 7m/s @ 100m. In 2014, The Crown State [60] compared MERRA wind speeds @50m and offshore meteorological data from 22 MET masts and 3 LIDARs located in UK[2]. Hourly MERRA wind speed @50m for 17 of 18 sites[3] had underestimated values varying between 3,6 to 13,1% of the real value. Only one site had an overestimation of 2%. For all sites, an average under-prediction of 7% of the value was calculated. For the evaluated sites, it was also concluded that MERRA over-predicts hourly wind speeds below 4-5m/s and under-predicts wind speeds above these values. This is re-confirmed while checking the maximum hourly wind speeds and it was concluded that, on average, MERRA under-predicts these maximum wind speeds in 20%. However, in some months, under-predictions exceeding 60% were found. The under-estimation tendency of MERRA was also exhibited in a paper released by Carvalho et al. [67] in 2014. Offshore wind speeds from five buoys measuring wind speeds @ 3m in the coast of Portugal and Spain were compared to MERRA. Negative hourly biases (underestimation) were found on MERRA wind speeds in four of the five buoys. Interestingly, in average, wind speeds below 4m/s had a positive bias of 0,8m/s; from 4 to 8m/s the bias was -0,47m/s; from 8 to 12m/s it was -1,46m/s; for speeds greater than 12m/s, the bias was -2,08m/s. In 2014, Cannon et al. [68] compared hourly MERRA wind speeds @ 10m to 328 meteorological stations of the network MIDAS in UK. It was showed that there was a slight systematic overestimation for wind speeds below 6m/s, a moderate underestimation for speeds ranging from 6 to 20m/s and a large one for speeds over 20m/s. As exhibited in Figure 22, when station over 300m above level were not considered, the underestimations were much larger. This was explained as a result of the smoothed topography of MERRA which leads to artificially low wind speeds for stations at high altitudes.

[1] Depending of the month, different soundings stations for checking were selected. Data extrapolated to 100m
[2] MET masts height ranging between 43 and 110m. LIDARS with data up to 301m. Each instrument had data ranging from 0,2 to 8,5 years
[3] With mean speeds @50m from 7,7 to 12m/s

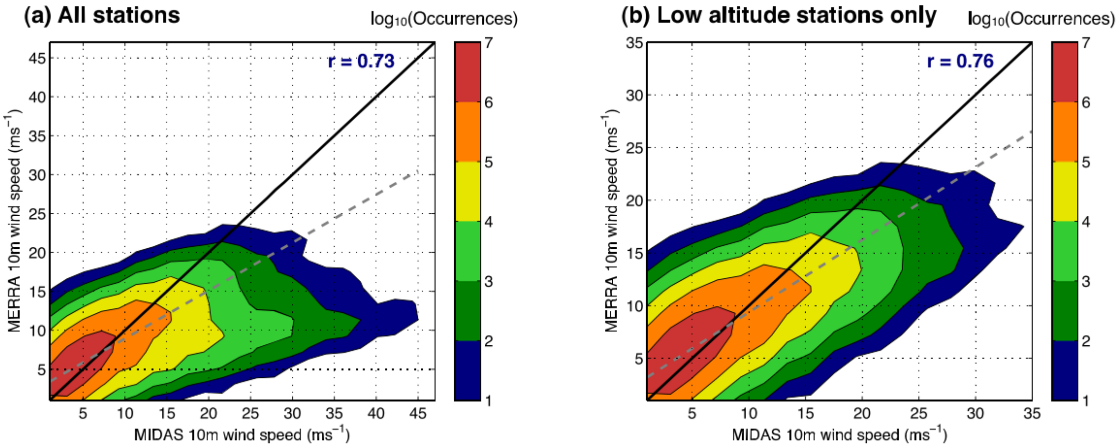

Figure 22: Scatter plot between MIDAS wind speeds @10m and MERRA wind speeds @10m for (reft) all the 328 stations and for (Right) stations below 300m above sea level in UK. Cannon et al. [68]

In 2015, Rose and Apt published a paper [69] relating Reanalysis data to wind power. It was point out that the relatively low spatial resolution on the Reanalysis models smooth the terrain, which is also responsible for enhancing the wind speeds. As a result, these models likely under-predict measured wind speeds in locations with complex terrain. In 2015, Ritter at al. [59] found a correlation coefficient always greater than 0,81 between MERRA wind speeds and wind measurements in Germany. In 2015, COWI presented in its report [19] the wind speeds @50m from a MET mast in the Guajira, Colombia, nearby the wind site of this study called Guajira. A mean wind speed of 7,5m/s between 2007 and 2013 was found. This magnitude is quite similar to the one of the present study for the same period[1], 7,38m/s. It shows a quite good performance of MERRA in this flat coastal region of Colombia.

Solar radiation

Although the solar resource has not been studied as the wind resource because of the –almost-linear relation from irradiation to power production (see subsection 4.6) and since MERRA reanalysis is not a traditional data source for photovoltaic power modelling, some papers have been written about the MERRA performance on it. In 2011, Yi et al. [70] validated the daily incident solar radiation from MERRA with the surface radiation budget (SRB) from the Global Energy and Water Cycle Experiment (GEWEX) between 2000 and 2006. As exhibited in Figure 23 on the left, MERRA presented mainly overestimations over South America of up to $5MJ/m^2/day$, equivalent to an average of approx. 58 W/m^2. However, for some regions in South America, MERRA also presented underestimations of the same magnitude. This was explained with cloud-modelling schemes used in Reanalysis. Furthermore, due to the coarse spatial resolution, temperature fields can also be significantly biased over complex and heterogeneous terrain and locations with persistent cloud cover.

[1] For 2001-2014 the mean wind speed @50m found is 7,66m/s

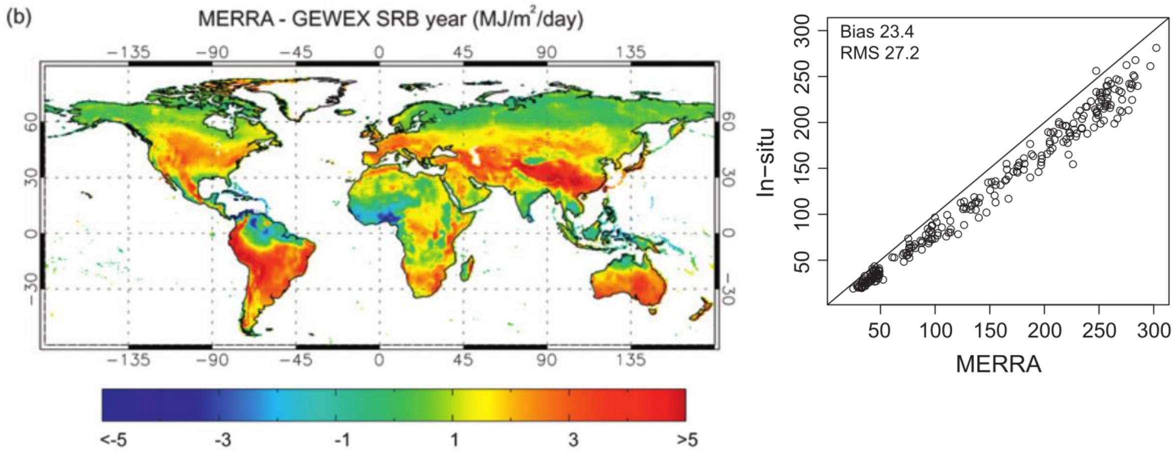

Figure 23: (Left) Annual biases between MERRA daily incident solar radiation and GEWEX-SRB for 2000-2006. Units in [MJ/m²/day]. Yi et al. [70]. **(Right) Scatterplot of MERRA surface incident shortwave radiation and in-site measurements in Czech Republic. Units in [W/m²]. Juruš et al.** [71]

In 2013, Juruš et al. [71] compared MERRA surface incident shortwave radiation with one measurement station in Czech Republic. An overestimation of the monthly resource for the period 1985-2005 was found (bias of +23,4W/m², as shown in Figure 23 on the right). Similar positive biases were found in 4 of 5 sites in Austria and Germany. For the fifth site, an underestimation was observed (-32,7W/m²). This site was located over the Alps at 3.105m above sea level not as the others below 1.000m. In 2014, Boilley and Wald [72] analysed daily shortwave radiation of MERRA with six in-situ measurements (Baltic Area, France, Eastern Europe, North Africa, Mozambique, Equatorial Atlantic) and found overestimations of MERRA compared to the measurements with biases of up to +21% in 5 of the sites. An underestimation was found for one site with a bias of up to -7%.

7.1.2 Correlation of data

In Sweden [1], In 2011, Liléo and Petrik [73] compared wind speeds from three different Reanalysis data sets (NCEP/NCAR, MERRA and CFSR) to 25 measurement masts. The Pearson´s correlation coefficients, R, between the wind speeds from 19 grid points of MERRA and the observations were found to be between 0,75 and 0,89 on an hourly basis [2]. In 2012, Jimenez et al. [74] compare wind measurement of 5 sites (Turkey, Romania, Scandinavia, Poland, Brazil) with data from the NCEP/NCAR and MERRA. The average coefficient of determination [3], R^2, was 0,86 for MERRA – varying from 0,81 in Brazil to 0,93 in Turkey. In 2012, Henson et al. [75], MERRA obtained correlation coefficients [4], between 0,75 and 0,87 compared with data from five

[1] Its highest mountain is the Kebnekaise, at 2.097m above sea level
[2] Although not clearly defined, it is inferred so
[3] Although called there correlation coefficient. It is inferred, but not clear, that hourly data was used for MERRA
[4] Infered to be R^2. Four MET mast had data for one year, one for 3 years.

MET mast in New England, northeaster USA. In 2013, Brower et al. [76] evaluated the quality of four Reanalyses datasets: NCAR/NCEP, CFSR, ERA-Interim and MERRA. First, the coefficients of determination, R^2, were calculated with data of 37 meteorological towers in USA, Europe and India. An averaged R^2 of 0,67 was assessed for MERRA using daily wind speeds. In 2013, Gkarakis [77], MERRA obtained correlation coefficients, R^2, between 0,68 and 0,94 compared to 22 MET towers with heights between 10-50m and with one to two years of data in Greece.

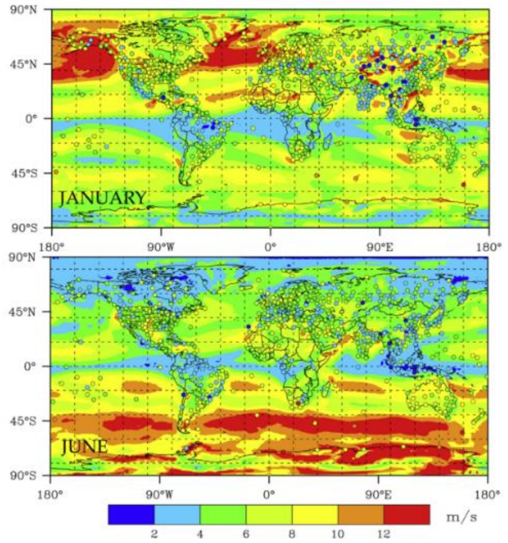

Figure 24: Simulated wind speed s@ 100m with the CATOR-GCMOM model. The circles are the sounding stations. Taken from [66]

In 2014, The Crown State [60] found hourly R^2 between MERRA wind speeds @50m and offshore meteorological data from 22 MET masts and 3 LIDARs located in UK[1]. They ranged between 0,64 and 0,93. Daily R^2 were between 0,80 and 0,97. Monthly R^2 were between 0,90 and 0,99. In 2014, Cannon et al. [68] compared hourly MERRA wind speeds @ 10m to 328 meteorological stations of the network MIDAS in UK. It was showed that in most cases MERRA accurately reproduces MIDAS wind speeds (correlation coefficient of 0,73). In 2015, COWI [19]found a R^2 of 0,85 between the wind speeds of MERRA a MET mast @50m in the Guajira, Colombia.

For the wind resource, in th investigation of Boilley and Wald [72] in 2014, the correlation coefficients from daily data ranged from 0,80 to 0,95 for four sites and from 0,27 to 0,77 for two sites. It is also announces that MERRA often predicts clear sky conditions while actual conditions are cloudy. The opposite is also true though less pronounced: actual clear sky conditions are predicted as cloudy by MERRA.

7.1.3 Trending of data

Brower [64], in 2006, provided an example for examining the internal consistency of the Reanalysis. The absolute error of a 10-year wind speed forecast was calculated as a function of

[1] MET masts height ranging between 43 and 110m. LIDARS with data up to 301m. Each instrument had data ranging from 0,2 to 8,5 years

the number of years of Reanalysis used to make the prediction in three sites, Figure 25, on the left. Depending on the site and the years taken, the absolute error varied significantly. This was also confirmed with a statistical analysis of all the model grid points in USA. The mean wind speed in a selected 10-years period was calculated as a function of the years of Reanalysis data taken. A typical curve of for one point along with data from a corresponding rawinsonde is shown in Figure 25, on the right. It was interpreted that longer historical periods do not necessarily result in better resource predictions[1]. On the contrary, relatively short period of data did not guarantee the lowest error but reduced the risk of extreme errors because this period had a balance between errors introduced by short-term weather fluctuations and by long-term trends and shifts. Beside this, compared with the rawinsonde errors in the same figure, it provided evidence that many trends and shifts in Reanalysis data are not real but are produced by the changing of the observational system.

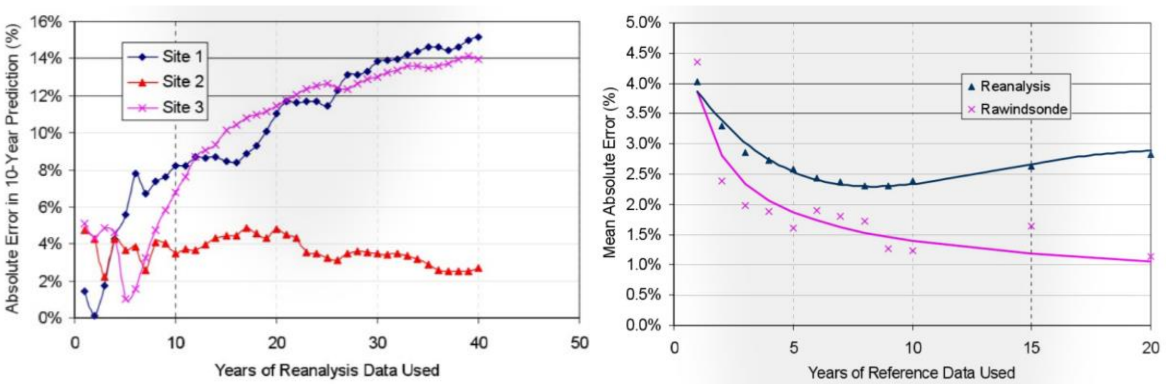

Figure 25: (Left) Absolute error of the 10years predicted wind speeds depending on the years of Reanalysis taken in USA-site 1, UK-site2 and Brazil-site3. (Right) Dependence of the error of a 10-year predicted mean wind speed on the number of years of Reanalysis used in a grid point in USA. Brower [64]

As pointed out by Brower in a paper [64] in 2006, there have been three main stages of development of the measurements included in Reanalysis programs besides significant regional and local changes in the observational system:

- 1948-1957: Main sources of upper-air data were just rawinsonde and pibal observations[2]. The density of observations were very low, especially in the southern hemisphere.
- 1958-1978: The modern global rawindsonde network was established. The number/density of observations grew steadily over many areas of the globe
- 1979-present: The global satellite observing system became operational. The number of satellites has steadily grown while new types of satellites/sensors have been introduced and older ones have been upgraded/improved.

[1] In the present study, 14 years were taken. Errors of 4-10% would expected for these three sites. However, the geographic characteristics of the three sites are not described. As a result, for example, if they were on coastal and flat areas, the errors expected for mountanedous regions as the Andes would be much larger.
[2] Radar wind –sonde and Pilot balloon

The study of Liléo and Petrik [73], in 2011, also shows a trend analysis for the period 1980-2009. The slope (k in the Figure 26) of the best-fitting linear regression for 6-hourly data for one point from each data set was computed. These k-values were divided by the minimum of all k-values (k_{min} in the same figure) showing mainly downward trends for MERRA over the territory, in blue, but also some points with upward trends, in brown. However, the weak downward trend reproduced by MERRA is in accordance with a study done by Wern and Bärring [78] in 2009, where it was concluded that the mean geostrophic wind speeds between 1951 and 2008 presented a downward trend.

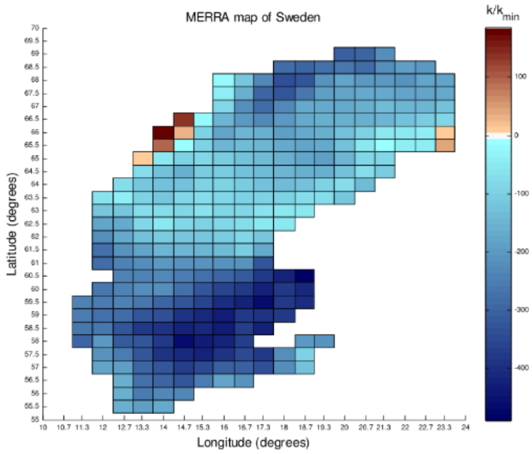

Figure 26: k/k_{min} plot for the MERRA grid points over Swedish territory showing the mostly downward (blue) but also upward (brown) trend between 1980 and 2009. Liléo and Petrik [73]

Brower et al. executed in 2013 [76] the Standard Normal Homogeneity Test (SNHT) and the Mann-Kendall trend test (MK) for inspecting their continuities and the trending behaviours respectively were also carried out. For these two test, 23 additional locations worldwide[1] were used. For the SNHT, MERRA had 28 failures, from the 60 location, between 1979 and 2012 but only one between 1998 and 2012. For the MK, MERRA obtained 42 failures between 1979 and 2012 and 33 between 1998 and 2012. It was concluded that there are more significant trends than significant discontinuities in data. These trends might reflect the influence of long-term climate oscillations or climate change as well as gradual changes in the observational systems. In 2015, COWI presented in his report [19] the mean annual wind speeds[2] of a MERRA grid point in the Guajira[3] since 1983 where a clear trend was noticeable:

[1] Additional to the 37 meteorological tower mentioned previously. One of these 23 locations is in Colombia
[2] It is understood that the wind speeds are @50m
[3] Same point as wind site Guajira in the present study

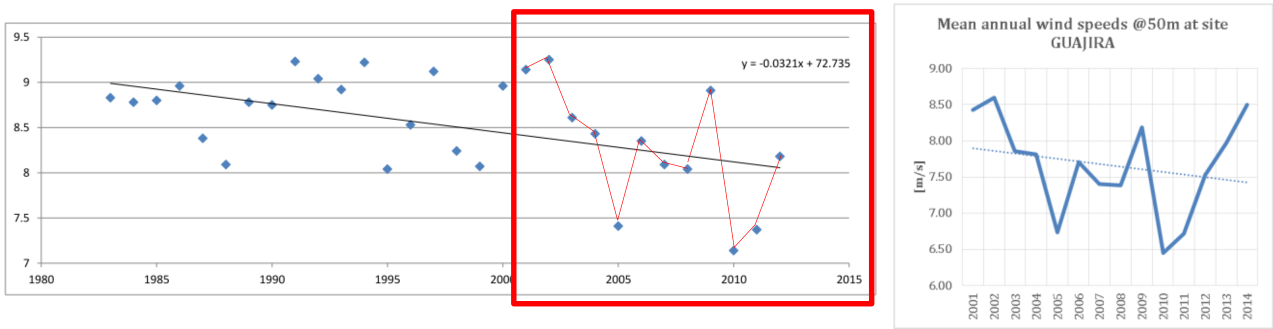

Figure 27: (Left) Screenshot of trend of MERRA wind speed for the wind site Guajira. Taken from[19]. Red lines drawn over it represent the (Right) calculated mean annual wind speeds @50m at site Guajira in this study.

There is also a difference on the magnitudes between both figures. It might be that COWI took wind speeds in other (higher) height or another pressure level. A de-trending was briefly presented in the study. However strong scientific arguments for this processing are not detailed in the report and are important to investigate in further studies. Although the present study covers only 14 years (Stream 3), slight trends can be seen in both the wind and the solar resources in several sites in the figures of the Appendix 11.6. No further investigations were done here.

7.2 Wind, solar and hydro resources

As shown in Figure 28, in a first overview, the obtained mean wind speeds have a similar general distribution compared to the layer 3TIER of the IRENA Global Atlas for renewable energy [61] to a certain extent. This confirms a good processing of the MERRA data. Lower winds are mainly presented in the Amazon rainforest as well as in the Magdalena plains. The highest winds are presented from the breakup point along the Eastern Andes and in the Guajira (point 12), north of the country. However, there are also several key differences: 1) Similar magnitude of the winds are presented in the Guajira and over the Andes by IRENA. However, MERRA exhibits a much higher resource in the Guajira than in the Andes; 2) MERRA present much lower winds in the Catatumbo area (between points 9 and 12) as IRENA; 3) IRENA displays high wind also at the end of the Eastern Andes and along the Central ones, contrary as in MERRA, where high winds are plotted only mostly on the Western Andes; 4) MERRA presents higher wind speeds in the Oriental plains, IRENA does not.

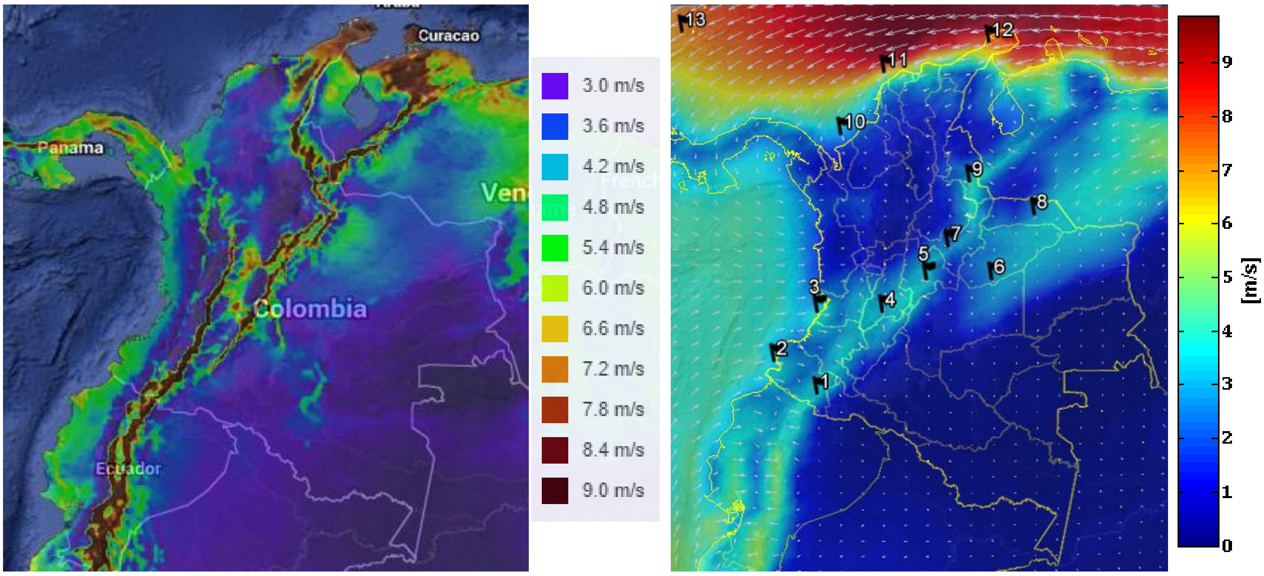

Figure 28: (Left) Mean wind speed @ 80m in [m/s] with 5km resolution. Taken from IRENA Global Atlas for renewable energy, 3TIER. (Right) Mean wind speed @ 50m in [m/s] from Stream 3 of MERRA

As the wind speeds are plotted at different heights (MERRA @50m, IRENA @80m), the magnitudes from MERRA are extrapolated[1] to 80m and listed in Table 31. By checking the extrapolated wind speeds @ 80m of the selected wind sites, a general under-estimation of the MERRA compared to the IRENA wind data is noticed for all the country but not for the Guajira area. A strong under-estimation appears mainly on areas over the Eastern and Central Andes (IRENA exhibits wind speeds up to around 9m/s). No under-estimation or a slight one is presented in the remaining points[2].

Wind site		Mean wind speed Stream 3 of MERRA [m/s]			
		Extrapolated @ 10m. Comparable to UPME-IDEAM map	@50m	Extrapolated @80m. Comparable to IRENA map	Extrapolated @100m. Hub height used for energy calculations
1	Nariño	2,82	3,73	4,00	4,12
2	Pacífico Sur	3,05	3,90	4,15	4,26
3	Buenaventura Sur	3,55	4,53	4,82	4,95
4	Tolima	2,70	3,58	3,84	3,96
5	Cundinamarca	2,89	3,83	4,10	4,23
6	Casanare	2,54	3,34	3,57	3,68
7	Boyacá	2,34	3,29	3,57	3,70
8	Arauca	2,61	3,43	3,67	3,78
9	Norte de Santander	3,33	4,41	4,73	4,88
10	Córdoba	2,28	3,31	3,61	3,76
11	Atlántico	4,38	6,18	6,71	6,96
12	Guajira	5,88	7,66	8,18	8,43
13	San Andrés	5,57	7,38	7,91	8,16

Table 31: MERRA wind speeds @50m and extrapolated to 10, 80 and 100m

As a second comparative information source, the wind atlas of the UPME-IDEAM (2006) [62] was consulted. It has a resolution of 10km and was developed with the mesoscale model MM5 based on 111 measurements over the country and is exhibited in the figure below:

[1] Using the logarithmic wind profile, Equation 7. Calculated directly with the online tool available in [96] based on the mean wind speeds @ 50m and mean roughness lengths showed in Table 13
[2] For San Andrés, point 13, IRENA considers a wind speed @ 80m of around 7,8m/s

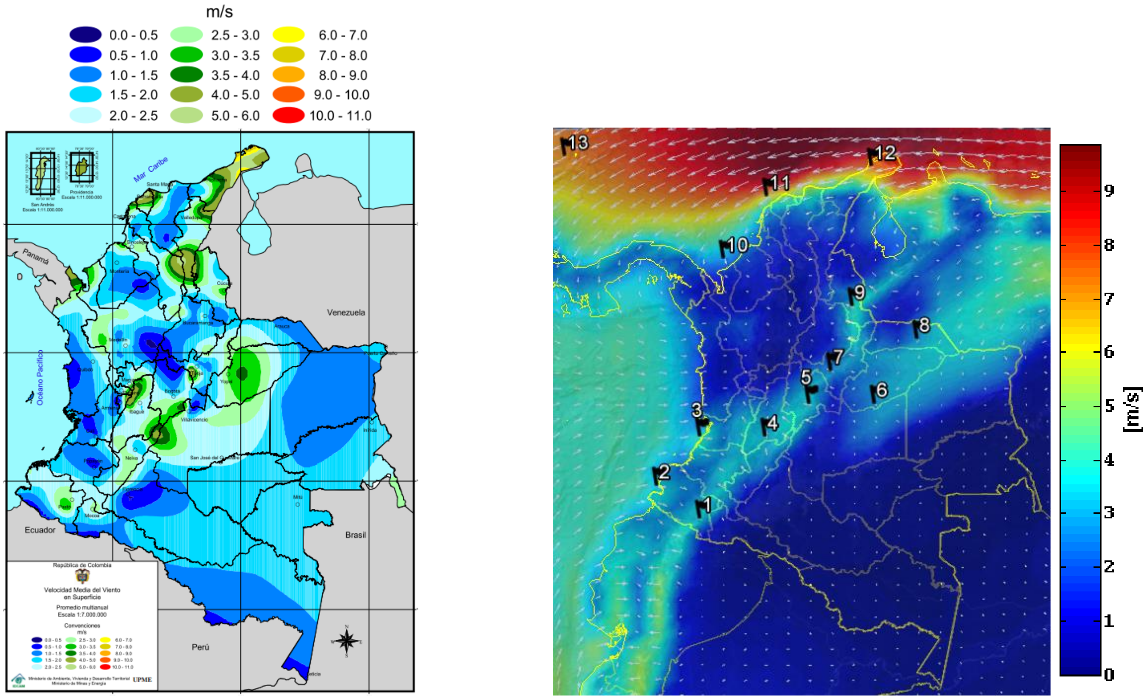

Figure 29: (Left) Mean wind speed @ 10m in [m/s] with 10km resolution. Taken from wind atlas UPME-IDEAM 2006. (Right) Mean wind speed @ 50m in [m/s] from Stream 3 of MERRA

In a first inspection, the wind speeds from the UPME-IDEAM atlas have a slightly similarity but to a much less extent than IRENA. Although in the Guajira and over Eastern Andes higher winds are presented in both plots, higher wind speeds in the Catatumbo region, middle of the Central Andes and in the end of the Western Andes are missing in MERRA. Furthermore, higher winds are presented in the Oriental plains in the UPME-IDEAM atlas, but much more to the west, compared to MERRA. When contrasting the magnitudes (UPME-IDEAM wind speeds @ 10m, thus extrapolated wind speed @ 10m are displayed in the Table 31), the resource in the Guajira has a minor under-estimation (UPME-IDEAM presents 6-7m/s). However, areas over the Eastern and Central Andes and the Catatumbo region present a strong difference while having wind speeds of up to 6m/s @ 10m which are not visible in MERRA (2-4m/s@50m). Similarly, but not that strong, the west of the Oriental plains as well as the end of the Western Andes have speed of up to 3,5-4m/s @ 10m, neither presented in MERRA. On the contrary, the points 2 and 3 show a slight over-estimation.

Similar as for the wind resource, the obtained solar insolations from MERRA were compared both with the 3TIER layer of the IRENA Global atlas, Figure 30, and with the solar atlas of the UPME-IDEAM (2005), Figure 31. In order to make the plots comparable, a changes of units of the MERRA data is provided in the Table 32.

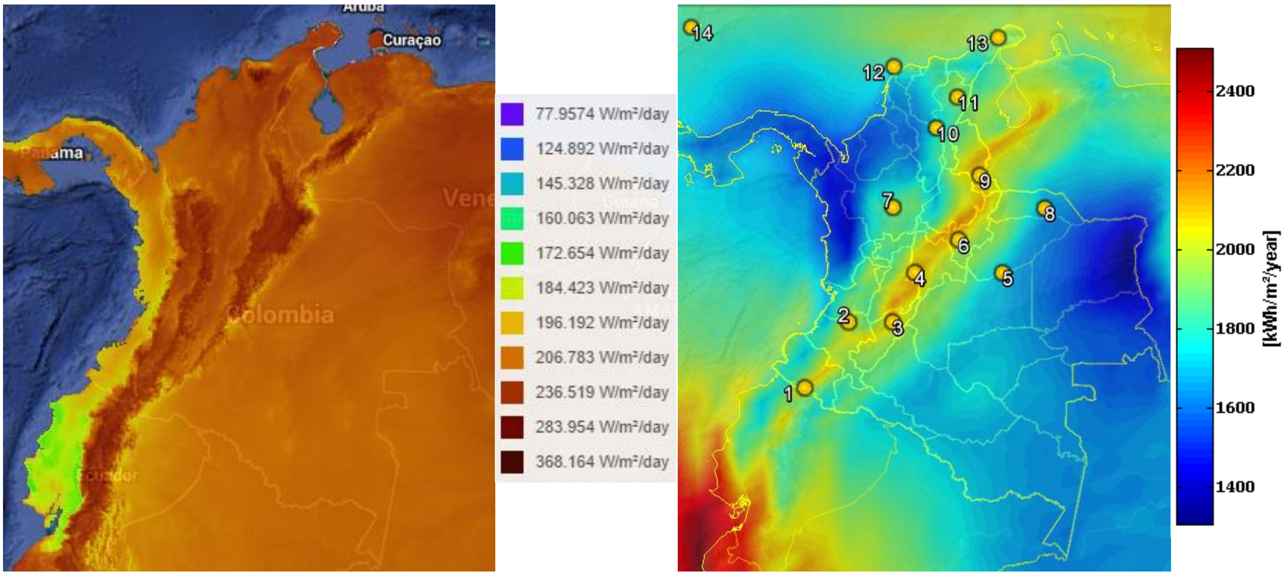

Figure 30: (Left) Mean Global Horizontal Irradiation, GHI, in [W/m²/day] with 3km resolution. IRENA Global Atlas for renewable energy, 3TIER. (Right) Mean annual solar surface insolation in [kWh/m²/year] from Stream 3 of MERRA

For the MERRA plot in the figure above, the scale has ranges from about 148 W/m²/day (1.300kWh/m²/year) to about 285W/m² (2.500kWh/m²/year), as calculated in the Table 32. The general distribution of the solar resource is similar for both plots and show a high resource in the Andes mountain chains and the Sierra Nevada de Santa Marta in the north. MERRA displays a larger resource over the Eastern Andes than for the Central and Western ones, contrary to IRENA, where the resource is similar on the three of them. For areas with a lower resource, there are some important differences. In IRENA, the lowest resource areas are concentrated in the west side of the Western Andes and on the east side of the Eastern Andes. For MERRA, the lowest resource areas are located on the extreme east and on the north-northwest of the country.

Solar site		Mean annual solar surface insolation Stream 3 of MERRA [kWh/m²/year]	Mean daily solar irradiation[1] [W/m²/day]. Comparable to IRENA MAP	Mean daily solar surface insolation[2] [kWh/m²/day]. Comparable to UPME-IDEAM map
1	Nariño Sur	2.082	237,5	5,70
2	Cauca	2.057	235,0	5,64
3	Huila	2.105	240,4	5,77
4	Cundinamarca Occidente	2.175	248,3	5,96
5	Casanare	1.695	193,3	4,64
6	Boyacá	2.092	238,8	5,73
7	Antioquia	1.875	214,2	5,14
8	Arauca	1.645	187,9	4,51
9	Norte de Santander	2.096	239,2	5,74
10	Bolivar	1.733	197,9	4,75
11	Cesar	1.939	221,3	5,31
12	Atlántico	1.833	209,2	5,02
13	Guajira	1.908	217,9	5,23
14	San Andrés	1.845	210,4	5,05

[1] Dividing the mean daily solar surface insolation by 24 hour and multiplying by 1.000
[2] Dividing the mean annual solar surface insolation by 365 days

Table 32: MERRA mean solar surface insolation and calculations to other units

Regarding the magnitude of the values, there is a slight under-estimation of MERRA compared to IRENA in the points 8 and 5. For the remaining points, the magnitude of the solar irradiation/insolation are quite similar between MERRA and IRENA.

The solar atlas from the UPME-IDEAM was also consulted. The distribution of the solar resource is surprisingly very different, compared to the obtained with the MERRA data. The areas with the highest solar resource are presented in the Guajira and in the Magdalena plains, north of the country, as well as in the Oriental plains. Some other areas over and close to the Eastern Andes also stand out.

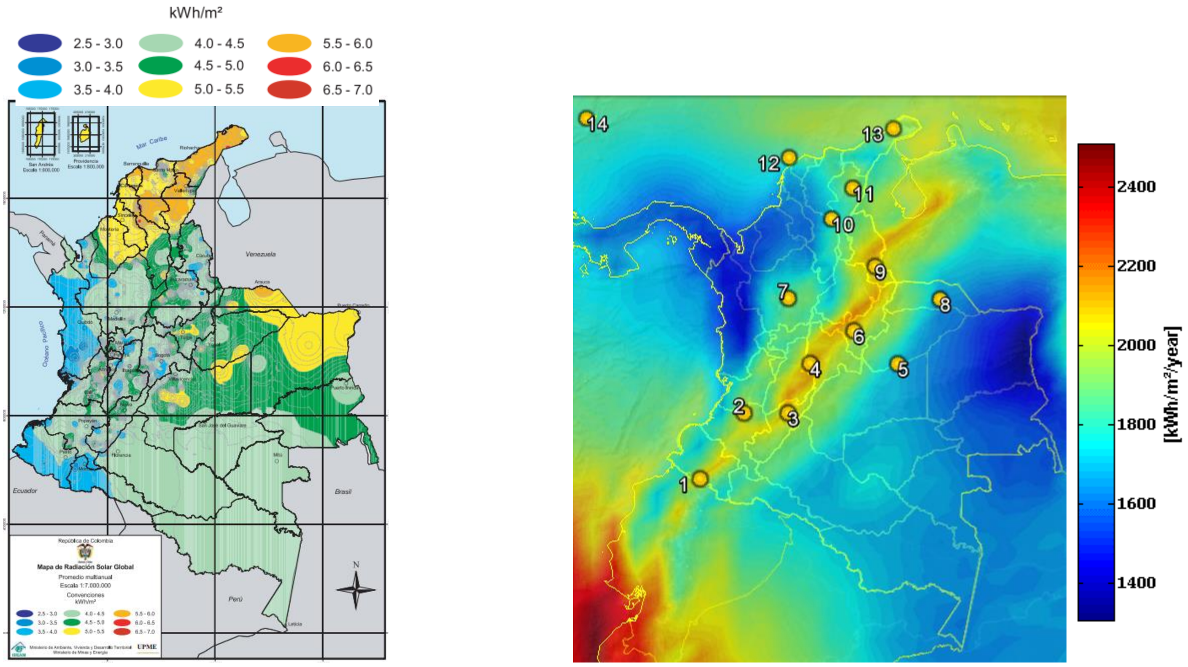

Figure 31: (Left) Mean Global Horizontal Irradiation, GHI, in [kWh/m²/day], unknown resolution. Solar resource atlas UPME-IDEAM 2005. (Right) Mean annual solar surface insolation in [kWh/m²/year] from Stream 3 of MERRA

The magnitude of the MERRA values outside the Andes are either similar (14, 23, 6) or under-estimated (13, 11, 10, 8, 5). Sites located over any of the Andes (9, 7, 4, 3, 2, 1) are over-estimations compared to the UPME-IDEAM solar atlas.

In general, the following remarks are presented:

- Although overestimations can also be observed in the different maps, mostly underestimations of the wind and the solar resource are produced by MERRA compared to the IRENA and the UPME-IDEAM atlas. Most of the differences should reside in the much detailed spatial resolution used (IRENA 5km, UPME-IDEAM 10km) compared with the ones of MERRA (55,3km x 74,2km). This surface smoothing can be observed if the Figure 33, the reality of the national geography, and the Figure 41 of the Appendix 97, the MERRA-seen topography, are compared. MERRA “sees” a much flatter topography with altitudes only up to about 3.000m above sea level, not as the real over-5.000m mountains. The Western and the Central Andes appear to be only one in MERRA and not separated mountainous systems, which have a strong impact of the wind resource. This was showed by several case studies in the section 7.1 where it was stated that Reanalyses might override several topographic structures which might enhance the wind producing strong negative biases (underestimation), especially over the Andes. In flatter areas such as the coast, the magnitudes are expected (as probed by COWI [19]) to be much closer to the reality. Regarding the solar resource, this surface smoothing also affects the estimation of the solar resource while having in mind that the development of clouds as well as the transportation of aerosols and gases with the air flows are also dependent of the topography and the terrain (affecting surface´s albedo) on the sites.

- Although the quality and the representativeness of the measurements included in the UPME-IDEAM atlas were not checked in the present study, most of the differences with the wind atlas should mainly reside in the local atmospheric circulations such as sea-land, mountain-valley and Foehn effects. Furthermore, the strong differences with the solar atlas also present questions about the clouds, gases and aerosols models included in MERRA for these inter-tropical areas and for these very complex topographies.

- As pointed out in the section 7.1, the observational system of MERRA is an important issue to describe its accuracy in certain site. One side, the quantity of data processed has strongly increased in the last decades. This can be observed in the Figure 42, Figure 43 and Figure 44Figure 44 of the Appendix 11.5. The observations used worldwide in 1979 were about 100.000 compared to the 1.500.000 in 2008 every six hours. As a result, trends (positive or negative) are likely to appear in several sites. On the other side, the spatial coverage of this observations impacts also the accuracy in certain areas. In Figure 45 the locations of the radiosondes measuring wind speed at 00:00GTM on the 1st of January of 2008 show an example of how few data is collected in general for South America and Africa, which might affect the accuracy of the data. However, in the figure, there are more observations in the Caribbean Sea than in the Andes and the Amazon, conveying likely to more accurate data for the coastal areas than for the Andes areas.

- The only way of approaching to the "true" magnitudes of the wind and the solar resource is by validating MERRA data with in situ measurement countrywide. While developing this study, it was known that information from meteorological stations around the country can be easily accessed for this purpose thanks to the IDEAM. This is very much recommended for future works.

- As described in the section 7.1, the ability of MERRA of capture time variations in the resource in a proportionate sense is a plus for this dataset. Most of the R and R^2 found worldwide where above 0,75, which are considered as a good sign. It can be inferred that, although there might be strong negative (underestimation) or positive (overestimation) biases depending on the site of study, MERRA data follows the measured data fairly good.

As a result, and having in mind that the R and R^2 found had different resolution (hourly, weekly and monthly), for the purposes of the present study of analysing the intra-annual and the inter-annual complementarity, the curves of the monthly wind speeds and solar insolation are a good approximation for an understanding of the resources in the country.

Regarding the hydro resource, as the river-inflows were taken directly from local data made available by XM, no further analysis of their accuracy in magnitude were executed and they are taken as true in the present study. However, comparisons of runoff and precipitation data from MERRA are highly recommended for future works.

7.3 Energy calculations

Wind and solar parks

The results of the monthly and Annual Energy Productions (AEP) obtained for the wind and solar parks were checked with engineering online tools ([79] [80] respectively). These tools were fed with the wind speeds and solar insolations obtained with MERRA. This confirmed a very good approximation of the calculations described in the subsection 4.6. However, as described before, due the likely underestimations on the wind and solar resource themselves, an intensification of the underestimations is transferred to the energy results due to the mathematical calculations. As a consequence, the AEPs exhibited in Figure 18, for the 99MW wind parks, and Figure 19, for the 50MWp solar parks, are expected to be very rough estimates with large underestimations.

These underestimation are especially intensified for the wind parks. The theoretical power density in the wind is proportional to the wind speed to the power of three[1]. For example, taken a base wind speed of 4m/s, if the "true" wind speed is 4,4 , 5, 6 or 7m/s (representing 10, 25, 50 and 75% more wind speed respectively) the differences in the theoretical available power will be 33, 95, 238 and 436% more respectively. It means the sensitivity from wind speed to theoretical wind power would be 3,3 , 3,8 , 4,8 and 5,8 respectively. In real life that differences in power will not be that strong. This is just the theoretical power. However, it shows why wind power is so sensitive to the wind speed. In the case of the solar energy, as described in the subsection 4.6 in the Equation 9, the power from PV cells has linear proportion to the solar irradiation (although not totally linear; several factor such as the temperature play a role on it) and its sensitivity might be around 1. As a result, solar power is not that sensitive to the resource as wind power is.

Furthermore, especially for the wind parks[2], they will not be placed in sites which have the average wind speed of an area of 55,3km times 74,2km (MERRA´resolution). They would be placed in areas where the wind speed is enhanced due to the topography and, thus, real wind

[1] Equation of power density in the air
[2] The theoretical power density in the wind is proportional to the wind speed to the power of three. For example, taken a wind speed of 4m

parks would have a much larger AEP than the here showed in these areas. Although in a less extent, for the solar parks would happen the same. Within the areas given by the coarse resolution of MERRA, the sites with less exposition to clouds (e.g. on the leeward of the mountains or on large plains) would be selected and larger AEP would be obtained.

Hydro power plants

Based on the information of the in-flows and the conversion factors made available by XM, the energy production of each hydro power plant was calculated. In order to carry out a doublecheck, the calculated AEP of some of the hydro power plants were compared to the real generation reported by XM in 2013. The results were fairly similar between them. Nevertheless, when plotting the monthly generation, a very important difference was observed in the patterns of monthly hydroelectric generation. An example is exhibited in the following figure:

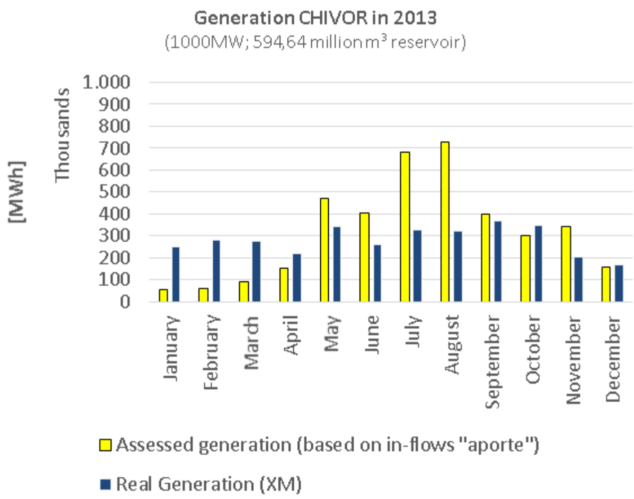

Figure 32: Real generation reported of hydro power plant Chivor (blue) and assessed generation based on XM in-flows (yellow)

The calculated AEP of the hydro power plant Chivor (1.000MW) in 2013 was 3.857GWh. The reported real generation was 3.372GWh. This difference was expected and should reside in the simplification executed with the conversion factors. The real operation of a large hydro power plant consider much more factors to have in mind. For the purposes of this study, the approximation of the AEP is valid. However, the monthly behaviours of energy production from the hydro power plants differ completely. This no clear relation between the river in-flows and the hydro production has been seen before in other studies [12]. The impact of large water reservoirs (in this case a reservoir of 594,61 million m^3) along with operational and, mainly, market strategies of the power plants might be the explanation to it and are out of the scope of the present study. As a result, no further investigation were executed and the energy of the hydro power plants selected was assessed based on the river in-flows because so, the real availability of the hydroelectric energy in the country would be described. Thanks to this assumption, the sensitivity of the hydroelectric energy calculated is close to 1. This because the in-flows are directly multiplies by a constant number (the conversion factor). However, the rated capacities of the hydro power plants were taken into account and, if the in-flows were larger than what the power plant could take, the excess of water was just dumped in the calculations.

7.4 Intra-annual meteorological dynamics

7.4.1 Weather patterns

The intra-annual patterns of the mean monthly wind speeds @50m of the 13 wind sites, mean monthly insolations of the 14 solar sites and the mean monthly in-flows of the 24 rivers plus the national group are presented in detail in the Appendices 11.6, 11.7 and 11.8 respectively. The diverse mean monthly patterns of the wind and the solar resource found in MERRA were compared to the *Climatologic Atlas* developed by the IDEAM in 2005 [81] along with its Appendixes [82]. Most of the patterns found have very similar behaviours along the years. Furthermore, an especially for the wind site Guajira, its monthly behaviour was also confirmed in other studies [4][5][19]. The just mentioned three studies presented also the mean monthly river in-flows patterns with confirmed the calculated in the present study based on data made available by XM. The wide variety of the monthly patterns all over the country of the resource are mainly driven by the global, regional and local meteorological dynamics influencing the weather in Colombia and are presented in the following subsection. However, before it, a brief overview of the geography of the country is presented.

Overview of the geography

The geography of Colombia has to briefly be presented. Please refer to the Figure 33. The massive Andes Mountains (coming from Chile, going through Bolivia, Peru and Ecuador and finishing in Venezuela) have a breakup point in the south of the country forming three mountain chains: the Western, Central and Eastern Colombian Andes. They are called the Cordilleras and have several altitudes over 5.000m above sea level. The highest peak in Colombia is the Pico Cristóbal Colón (5.776m), in the Sierra Nevada de Santa Marta in the north, sometimes considered also as part of the Andes. The lowest altitudes are concentred in the Amazon rainforest and the Oriental plains, comprising almost half of the country. Other low altitudes are over the Pacific coast, on the valleys between the Andes and on the Magdalena plains. In the breakup points of the Andes, the largest river in Colombia, the Magdalena river, starts its journey between the Central and Eastern Andes. The second one, the Cauca river, starts between the Western and Central Andes. Both crossing the country up to the north. Besides this, the country is surrounded by the Atlantic Ocean, or also called Caribbean Sea in this region, on the north and by the Pacific Ocean on the west. To the southeast, the gigantic Amazon rainforest extents from Brazil.

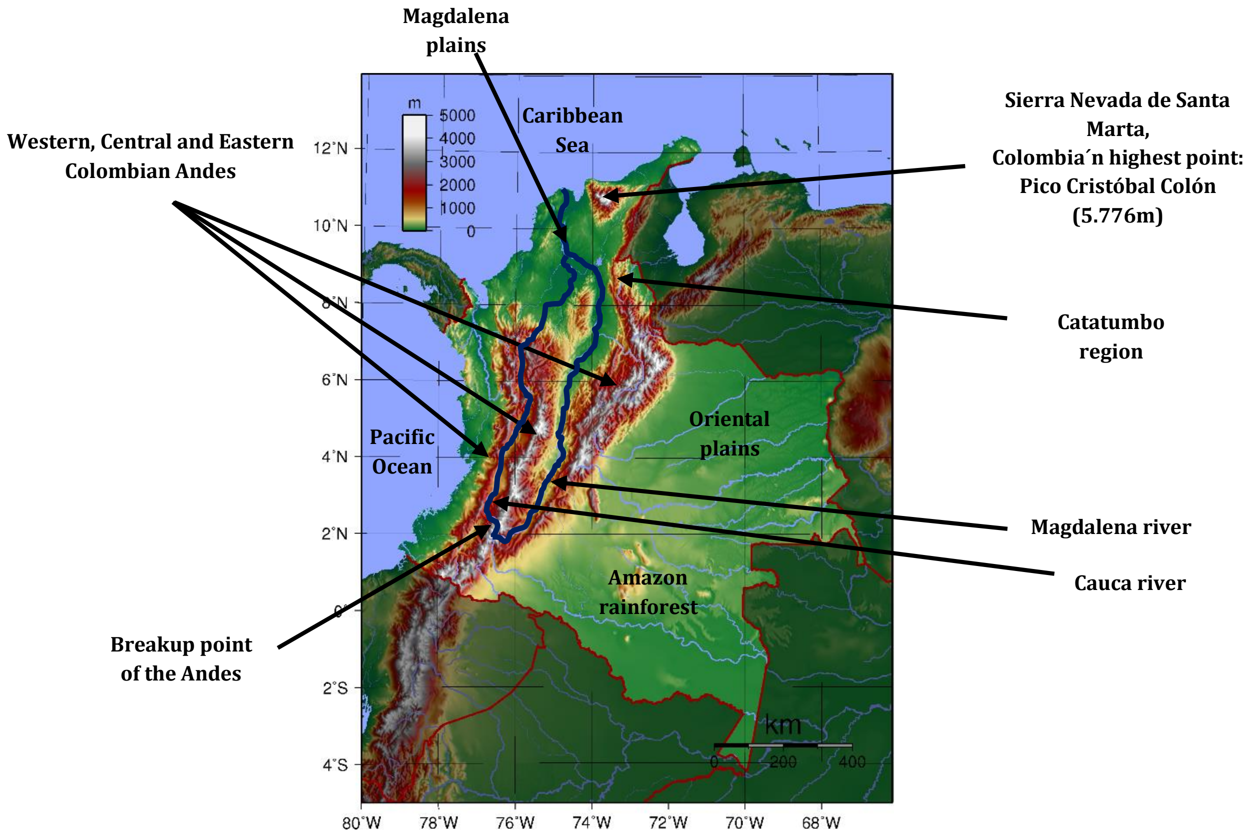

Figure 33: Geography of Colombia. North upwards. Taken from [83]

Global atmospheric circulations

As country is located close to the Equator, between the Tropics[1] [81]. As the Equator is the Earth´s area where most of the solar radiation is received, this energy is heating up the air on the surface forcing it to rise[2] (convective flows), producing a low-pressure area around the Earth. This narrow global low-pressure belt is called the Doldrums or the ITCZ (Inter-Tropical Convergence Zone). In the ITCZ, this ascension allows air to expand and transfer heat to the surroundings and thus, to cool it down. This cooling of the air favour condensation and the development of clouds. Consequently, stronger and more frequent thunderstorms and precipitations in this area are produced. After cooling down, at high altitudes, between 10 to18km [84], at the end of the Troposphere[3], air flows polewards and sinks around 30° north and south, just after the Tropics, producing a subtropical high-pressure belt and forcing air to flow back on the surface towards the Equator. The descending air flows on the surface, are deflected to the west in both hemispheres by the Coriolis force, due to the Earth´s rotation. These flows are called the Trade winds [81] and are the governing global flows in the inter-

[1] The Tropics are the last lines where the sun is exactly over it in the year. The Tropic of Cancer is approx. 23° north of the Equator. The Tropic of Capricorn is approx. 23° south of the Equator

[2] Molecules in parcel of hot air move faster than in cold air causing an expansion and thus, a lower density (lower pressure). Buoyance forces that result from this density variation force this parcel to rise.

[3] Lowest portion of the atmosphere containing approx. 99% of water vapour at aerosols of the atmosphere.

tropical region. As a result, Trade winds flow predominantly from the northeast, in the northern hemisphere, and from the southeast, in the southern hemisphere, and converge in the Equator. Finally, in the Equator, the convective flow forces these Trade wind to rise again, producing calm winds in the surface. This atmospheric circulation is called the Hadley cell and is shown in the Figure 34 on the left.

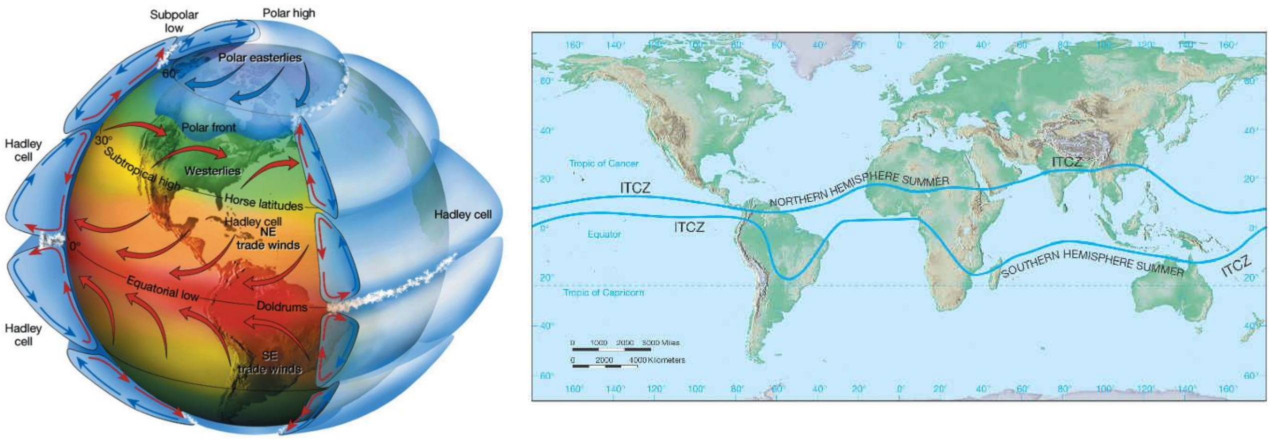

Figure 34: (Left) Global circulation of the atmosphere. Taken from IDEAM [81]. **(Right) ITCZ lines (blue). In the northern hemisphere summer the ITCZ is in its extreme north (Jun-August). In the southern hemisphere summer the ITCZ is on its extreme south (December-February). Taken from** [85]

As shown on the right part of the Figure 34, the ITCZ is moving throughout the year depending of the Earth´s position to the Sun: in December-February the area is on its extreme south, in June-August on its extreme north[1]. The location of both extremes is not clearly defined. However, a rough approximation can be observed in the previous figure. As a result, when the ITCZ is on its extreme south, it is more distant to northern regions of Colombia generating stronger winds and more solar insolation in the north. Furthermore, more clouds and precipitations are expected in the south. On the contrary, when the ITCZ is on its extreme north, it is more distant to the south of Colombia producing stronger winds and more insolation in the south. Moreover, more clouds and precipitations are expected in the north. The regions in between, observe the ITCZ twice during the year making them to have bi-modal behaviours. These dynamic can be seen in all the monthly behaviours of the wind speed @50m, solar insolation and river-inflows exhibited in the Appendices 11.6, 11.7 and 11.8 respectively[2], having in mind the location of the sites presented in Figure 7, Figure 9, Figure 11 and Figure 12.

For the wind resource:

- In the north of the country, the wind sites 10 Córdoba, 11 Atlántico, 12 Guajira, 13 San Andrés present stronger mean monthly wind speeds when the ITCZ is on its extreme south

[1] In theory, the extremes should happen on the solstices in June and December. However the effects are seen in months later due to times of heat transfer from and to the land, atmosphere and oceans
[2] Please remember that they all are listed from south to north

(December February). On the Oriental plains the wind sites 6 Casanare and 8 Arauca present the same behaviour.

- In the south and centre of the country, the wind sites 1 Nariño, 2 Pacífico Sur, 3 Buenaventura Sur, 4 Tolima, 5 Cundinamarca and 7 Boyacá present stronger mean monthly wind speeds when the ITCZ is on its extreme north (June-August)
- The wind site 9 Norte de Santander presents a bi-modal behaviour

For the solar resource:

- In the north of the country, the wind sites 10 Atlántico, 13 Guajira, 14 San Andrés present more monthly solar surface insolation when the ITCZ is on its extreme south (December February). Although the solar sites in the north 10 Bolivar and 11 Cesar and the solar site in the Oriental plains 8 Arauca present bi-modals behaviour, the component of the ITCZ is stronger from December to February.
- In the south and centre of the country, the solar sites 1 Nariño Sur, 2 Cauca, 3 Huila and 4 Cundinamarca Occidente present more monthly solar surface insolation when the ITCZ is on its extreme north (June-August). The solar site in the north-east 9 Norte de Santander presents a similar behaviour
- In the Oriental plains, the solar sites 5 Casanare and 7 Antioquia presents mainly bi-modal behaviours. The solar site 6 Boyacá presents also this behaviour.

Consequently, the ITCZ and the Trade winds are found as the main drivers of the intra-annual patterns of the wind and solar resource in Colombia.

For the hydro resource:

As the in-flows of a river have much more complexes dynamics on the time such as the topography the river follows, types of soils, underground waters, underground reservoirs, evaporation, among others, the precipitation induced by the ITCZ cannot easily explain the intra-annual behaviours of the river in-flows. These intra-annual hydrology dynamics are out of the scope of this study and therefore, they are taken as a fact. However, it can be pointed out that:

- Hydro power plants in Colombia are mainly located in the center and the south of the country, over the Andes. In the flat coastal areas in the north (e.g. Magdalena plains), there is no possibility of the construction of large hydro power plants because of the flat topography. As a result, when the ITCZ is moving from its extreme south towards the north in the first semester of the year and coming back on the second semester, the precipitation is larger over the location of these hydro power plants. An example is exhibited in the Figure 35, where the precipitations of the city called Neiva, over the Andes in the south-center of the country, are stronger in March and November (bi-modal behaviour). However, the peak of the in-flow of the river Magdalena Betania is observed in in June. These in-flows presented are taken in the dam Betania, located approx. 30km south from Neiva. The spring is located approx. 180km south. Consequently, the mentioned factors of the complex dynamics in the river in-flows cannot be directly explained by the ITCZ.

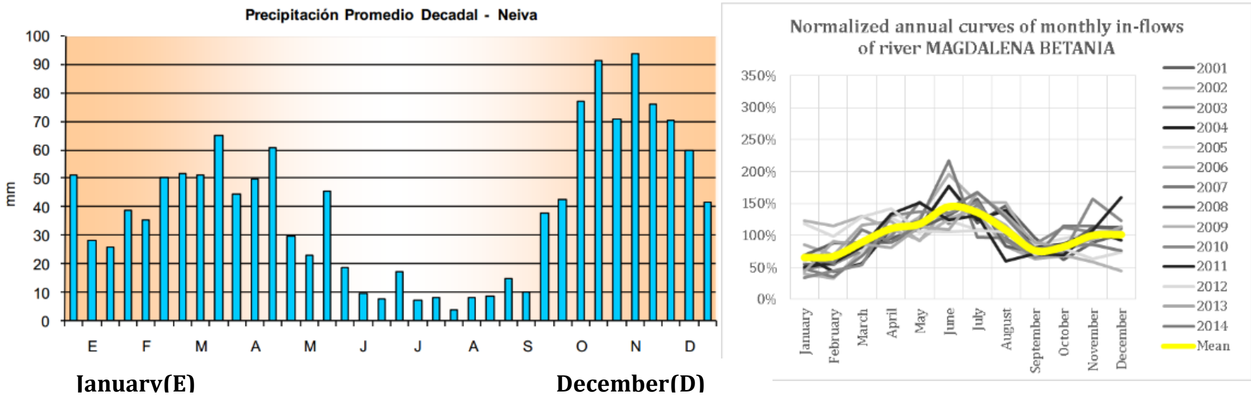

Figure 35: (Left) Precipitation along the year in Neiva. Taken from [82]. **(Right) mean monthly river in-flows of the river Magdalena Betania based on XM data. The city Neiva is about 180km away from the spring of this river but only 30km from the dam, where these flows are taken**

By taking a look on the figure, it is important to remark that Colombia might be the country in the world with the thinnest distance between both ITCZ extremes. However, this affirmation requires a further investigation out of the scope of this study.

Another large scale weather phenomena is the El Niño Southern Oscillation (ENSO)[1]. This has not been studied in detail because the present study assumes that the changes in the hydrology of the country are already visible in the hydro resource indexes presented in the section Meteorological Results. However, future investigations should include this phenomena in detailed, especially in topics related to. inter-annual complementarities.

Regional and local atmospheric circulations

On a regional scale, the most influencing atmospheric system on the weather in Colombian are the Easterly Waves. These are created by low-pressure systems of short duration on the north Atlantic, which are responsible for tropical cyclones (counter-clock circulation; depending on the scale, also called hurricanes). Occurring specially between June and November. Although the Easterly Waves are distant from Colombia, they have some impact in the northern regions. This might be the explanation of increase presented in July in the mean monthly wind speed in the sites Atlántico, Guajira and San Andrés in the Figure 56, Figure 57, Figure 58 respectively. Furthermore, for the same three sites, the mean monthly solar insolations have also a rise in the same month as observed in Figure 70, Figure 71 and Figure 72. This is likely because this

[1] It occurs when for at least five consecutive months, the three month running average mean of the sea surface temperature anomaly in the region between 5°N- 5°S and 150°W-90°W is above (below) 0.5 (-0.5) [18]

tropical cyclones push the air masses (including clouds) more to the south and the west of the country allowing more solar radiation to get to the surface. There are other atmospheric systems such as the Synoptic Systems of the Pacific and the Amazons which are not covered in detail in this study.

Apart from global and regional systems, the meteorological resources in Colombia in the surface[1] are strongly impacted by local conditions and friction produced by the complex topography, governed by the variety of heights of the three Andes Cordilleras, the two massive water bodies in the north and the west and the Amazon rainforest in the southeast. Due to different temperature changes of sea and land, sea-land breezes might occur in coastal areas, with more intense winds flowing towards the sea in the night. In the Andes, same effects are present: mountain-valley breezes, producing ascendant winds during the day and descendent in the night. Moreover, wind speeds tend to increase with the height due to friction reduction in the Andes and thus mountainous areas might have larger wind speeds compared to low areas. These Cordilleras, especially the Eastern one, and the sizable Amazon rainforest present a large barrier to the southeast Trade winds which generates a weakening or a strengthening of the wind flows on the leeward areas depending of the orientation and shape of the topographies. Furthermore the Foehn effect, which produces strong, dry and warm winds on the leeward and cloudiness on the windward, are also presented due to this variety of orography. However due to the resolution of MERRA, these local effects cannot be observed in the intra-annual patterns found in the present study. Further investigations and validations with in situ data are highly recommended for understanding theses effects.

7.4.2 Intra-annual complementarities

Hydro-Wind

The mean intra-annual correlation coefficients, R, between monthly wind speeds @50m and monthly river in-flows in the 19 selected hydro power plants are presented in the Table 19 in the section Results. The meteorological dynamics along with the complex dynamics in time of the hydrology of the rivers of the country present a wide variation of positive, negative and not correlated coefficients between pairs. With some exceptions, the regions with large negative correlation coefficients (>0,5) are mostly found between:

[1] Also called Planet Boundary Layer (PBL) and referring to up to 2km over the surface

River in-flows Location along the country (geographic area)	Wind speeds Location along the country (geographic area)
North (Central Andes) Rivers flowing to San Carlos, Playas, Guatapé, Jaguas, Tasajera, Guatron, Porce II, Porce II **North (Getting to the coast)** Rivers flowing to Urrá	**North (Magdalena plains and coast)** Wind sites Atlántico, Cordoba and Guajira **East (Oriental plains)** Wind sites Casanare and Arauca
South (Western Andes) Rivers flowing to Salvajina, Alban, Calima	**South and centre (Eastern Andes)** Wind sites Nariño, Tolima, Cundinamarca, Boyacá

Table 33: Summary of the regions with large monthly (intra-annual) complementarities between wind speeds and river in-flows

On a national level, the highest negative correlation coefficients were found in the wind sites on the Oriental plains (Arauca with 0,69 and Casanare with 0,59) and over the north coastal area (Córdoba with 0,63 and Atlántico with 0,56).

Hydro-Solar

The mean intra-annual correlation coefficients, R, between monthly solar surface insolation and monthly river in-flows in the 19 selected hydro power plants are presented in Table 21 in the section Results. Again, the meteorological dynamics along with the complex dynamics in time of the hydrology of the rivers of the country present a wide variation of positive, negative and not correlated coefficients between pairs. With some exceptions, the regions with large negative correlation coefficients (>0,5) are mostly found between:

River in-flows Location along the country (geographic area)	Solar insolations Location along the country (geographic area)
North (Central Andes) Rivers flowing to San Carlos, Playas, Guatapé, Jaguas, Tasajera, Guatron, Porce II, Porce II	**North (Magdalena plains and coast)** Solar sites Bolivar and Cesar **North (Central Andes)** Solar site Antioquia **East (Oriental plains)** Solar sites Casanare and Arauca
South (Western Andes) Rivers flowing to Salvajina, Alban, Calima	**South and centre (Eastern Andes)** Solar sites Nariño Sur, Cauca, Huila andCundinamarca Occidente

Table 34: Summary of the regions with large monthly (intra-annual) complementarities between solar insulations and river in-flows

On a national level, the highest negative correlation coefficients were also found in the solar sites on the Oriental plains (Arauca with 0,73 and Casanare with 0,60) and over the north of the Central Andes (Antioquia with 0,63).

Hydro-Wind and Hydro-Solar

As in the previous subsection, the ITCZ could explained the correlation coefficients between the wind speeds in the north and the precipitations in the south and vice versa. The same for the relation between solar irradiations and precipitations. However, likely due to time delays happening in several months in the formation of river in-flows due to the complex hydrological dynamics in the three Andes Cordilleras, not included in this study, the ITCZ cannot explain by itself the correlation coefficients found between these three variables. As a result, further studies in the formation of the hydrology over the Andes are needed to fully explain the results found. When translated into wind/solar and hydroelectric energy, although there are minor changes in the coefficients of the correlation matrices (Table 27 and Table 29), the general distribution of the correlation coefficients along the country does not change. However, without complete explanations about the correlation coefficients between wind speeds/solar insolations and river in-flows, explanations between monthly wind/solar energy and monthly hydroelectric energy cannot be done.

It is interesting how the strongest intra-annual complementaries of the three resources are. For both, correlations mainly north to north and south to south/centre were found. As a consequence, wind and solar parks might be able to backup hydro power plants in regions nearby on times where these regions have critical low hydrology. This entails a very important factor in terms of energy transport in the transmission system. However, the intra-annual complementarity is still not valued by the Colombian energy market. In the current regulation, the Reliability Charge[1] assess the firm energy of a wind park just with 6% of the rated capacity. There is not even a calculation for solar parks. If an additional charge (or a change in the current Reliability Charge), would be created, such as a Complementarity Charge[2], it would encourage power plants based on other renewables resources such as wind and solar power by recognizing the benefits of the intra-annual complementary of a mix from a generator. This having in mind the capacity of hydro power plants with reservoirs of balancing systems with high fluctuations on their generations such as the wind and solar parks [89].

7.5 Resource indexes and IAVs

The Inter-Annual Variability (IAV) is a measure of the variation from one year to the next. When financing a power plant, the IAV of the resource can be the largest factor to determinethe amount of financing provided. As to ensure more revenue than required each year to repay the debt (debt service coverage ratio), lenders require a level of conservatism dictated by the amount of annual variation expected from a project [60] [90].

[1] "Cargo por Confiabilidad": Due to the high dependence of hydropower, a mechanism was introduced in 2006 in the Colombian energy market aiming to ensure the reliability in the supply of energy in the long-run by preventing future shortages. This scheme is the Reliability Charge. In conditions of critical energy supply the generators are remunerated with a stable payment during dry periods [104]. In exchange, the generator commits to deliver determined quantity of firm energy when the energy spot price is higher than the pre-determined level. This commitment is backed by different generation capacities, mostly hydro power plants and thermal power plants [105]. The firm energy for this Reliability Charge refers to the maximum energy that a power plant can provide continuously in conditions of critical hydrology [106]. For thermal (coal or gas) power plants, this firm energy is above 90% of the rated capacity; for hydro power plants between 30 and 55%; for wind parks, the factor is calculated as 6 % [107][108] (If the site has less than 10 years 10-minutes-measurements). As a result, this scheme encourages investment mostly in thermal and large hydro power plants, but not in wind-, solar- or small hydro power plants.

[2] Term mentioned by ISAGEN in the general review

A summary of the resource indexes as well as their Inter-Annual Variability (IAV), found in the Table 14, Table 16 and Table 18, is presented in the Table 35. Although the energy indexes and their IAVs are also presented, due to the uncertainties presented in the subsection 7.1, these are first estimates and might be the base of future studies. The findings in the present study can provide a first guidance of the overall variability of the wind and solar resource at the time span of the analysis is 1 4 years. It is assumed that financing of hydro power plants is a already established and known topic in Colombiandue to its large share on the energy matrix and thus it is not analysed in detailed. However, is it remarable the high variability that some rivers presented in the analysis. This migth have happen because of the ENSO. However, this is not covered in this study. Furthermore, as presented in the table below, the solar resource is less variable than the wind resource, while having lower IAVs. As a result, a further analysis is presented only for the wind resource.

	Resource		Energy	
Minimum and maximum values found	**Index**	**IAV**	**Index**	**IAV**
Wind energy (MERRA)	84 – 112%	2,9 - 8,5%	59 - 140%	7,7 - 22,7%
Solar energy (MERRA)	89 – 109%	2 - 6,2%	90 - 108%	1,9 - 5,3%
Hydroelectric energy (XM)	45 – 231%	8,2 - 43,7%	61 - 148%	6 - 23%

Table 35: Summary of the resource and energy indexes found

The IAVs of the wind resource presented are within the ranges found in the literature. In 2010, Kapetanovic [91] presented IAVs of up to 6% for 10 years of surface winds (@10m) from the NCEP/NCAR Reanalysis in USA. In a presentation hold in 2011, Johnson et al. [90] mentioned typical IAVs for the wind speeds between 3 and 7%. For the energy production of a wind park, the IAVs were between 5 and 14%. In the study done by The Crown State [60], the IAVs were calculated for 6 offshore MET masts in UK which 4 years of data ranging from 1,5-6,6%. In the study of Brower et al. (2013) [76], the IAVs of other Reanalysis data, the ERA-Interim, was done for the wind speeds @ 80m over period 1988-2012. The study states that the Inter-Tropical Convergence Zone (ITCZ) is related to a high degree of wind variability producing IAV values approaching or exceeding 10% along the equator. Outside of this zone, the IAV appears to fall in a range of 2%-6%. The results are presented in the figure below; for the Colombian territory, the highest IAV, approx. 10%, are shown in la Guajira:

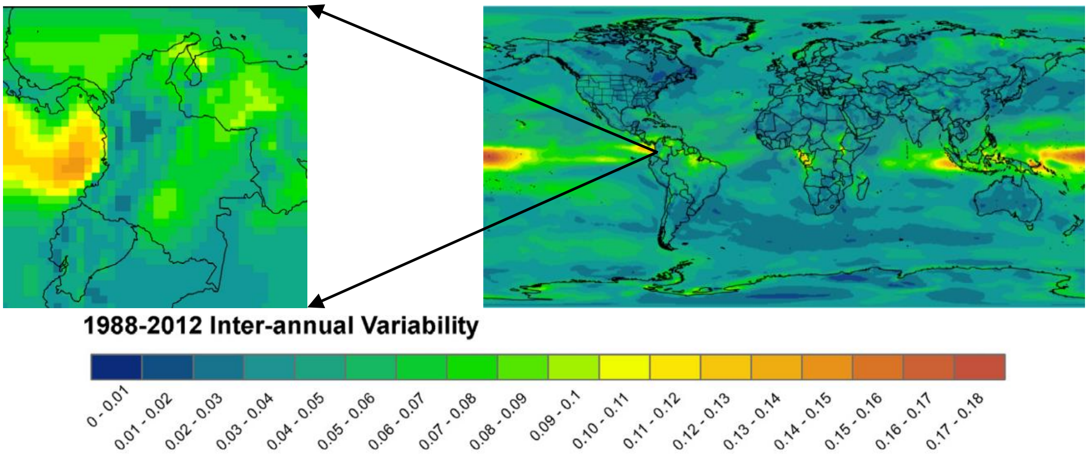

Figure 36: Inter-Annual Variability of wind speed @ 80m using the ERA-Interim Reanalysis for the period 1988-2012. Taken from [76]

This is confirmed in the presented study with an IAV for the Guajira of 8,5%. However the wind site Nariño (in the south) presents also an IAV of 8,4% that is not reflected in the graph. Furthermore, Brower showed that the average observed IAV was about 85% of the average ERA-Interim IAV, indicating a likely overestimation of the IAV by the ERA-Interim. MERRA presents a lower IAV than the presented by ERA-Interim in the Guajira. However, the contrary was presented in by COWI [12] where it was stated that the observed variation of the wind resource was higher than the one modelled by MERRA. As the statement did not clarify the time spans used and the time resolution, they cannot be directly compared to the present study. The IAV may arise if a larger number of years are taken due likely long-term climate oscillations. Thus the taken time spam is of high importance for future studies.

7.6 Inter-annual complementarities

Hydro-Wind

Similar as in the intra-annual complementarities, the mean inter-annual correlation coefficients, R, between monthly wind speeds @50m and monthly river in-flows in the 19 selected hydro power plants are presented in the Table 20 in the section Results. The meteorological dynamics along with the complex dynamics in time of the hydrology of the rivers of the country present a wide variation of positive, negative and not correlated coefficients between pairs. With some exceptions, the regions with large negative correlation coefficients (>0,5) are mostly found between:

River in-flows Location along the country (geographic area)	Wind speeds Location along the country (geographic area)
North (Central Andes) Rivers flowing to San Carlos, Playas, Guatapé, Jaguas, Tasajera, Porce II	**South, Centre, North (Eastern Andes)** Wind site Nariño, Tolima, Cundinamarca, Boyacá, Norte de Santander

Table 36: Summary of the regions with large annual (inter-annual) complementarities between wind speeds and river in-flows

On a national level, the highest negative correlation coefficients were found in the wind sites on the Eastern Andes (Tolima with -0,74; Cundinamarca with -0,67; Boyacá with -0,64).

Hydro-Solar

As for the intra-annual complementarity, the mean intra-annual correlation coefficients, R, between monthly solar surface insolation and monthly river in-flows in the 19 selected hydro power plants are presented in Table 22 in the section Results. Again, the meteorological dynamics along with the complex dynamics in time of the hydrology of the rivers of the country present a wide variation of positive, negative and not correlated coefficients between pairs. With some exceptions, the regions with large negative correlation coefficients (>0,5) are mostly found between:

River in-flows Location along the country (geographic area)	Solar insolations Location along the country (geographic area)
North (Central Andes) Rivers flowing to San Carlos, Playas, Guatape, Jaguas, Tasajera, Porce II	**South and Centre (Eastern Andes)** Solar sites Nariño Sur, Cauca, Huila, Cundinamarca Occidente and Boyacá
Centre (Eastern Andes) Rivers flowing to Prado and Pagua	

Table 37: Summary of the regions with large annual (inter-annual) complementarities between solar insolations and river in-flows

On the national level, the highest negative correlation coefficients were found in the solar sites on the Eastern Andes (Nariño Sur with -0,74; Huila with -0,69; Boyacá/Cauca with -0,61).

Lowest/highest years

In the Table 14, Table 16 and Table 18 a relation between the wind, the solar and the hydro resources can observed within these 14 years. In years of general low hydrology for most of the rivers (2001-2002), higher magnitudes of wind and solar resources where available on most of the wind and solar sites. In years of high hydrology (2011), the opposite is observed. This can be also observed in the graphs of several sites through the Appendices 11.6, 11.7and 11.8.

8 Conclusions

For Reanalysis data, the wind resource has been more studied than the solar resources in investigations worldwide. This due to the relation between wind speed and wind power and between solar irradiation and solar power. The first one is extremely sensitive because the theoretical power is related to the wind speed to the power of three and uncertainties would highly intensify. In the case of the solar power, the linear (although not completely linear because of factors such as the temperature) relationship between the solar irradiation and the solar power makes this relation to be not that sensitive. As a result, analysis of the wind resource are of more importance for the wind power than the ones from the solar resource for the solar power. This could be observed in the literature research executed in the present study.

The accuracy of wind and solar data from the MERRA, and in general from other Reanalyses, is very much site-dependent. In the case of the wind resource, several international studies presented more accurate magnitudes in areas of fairly flat terrain over large distances (including offshore areas). In complex terrains such as shorelines, hills and mountains the magnitudes might have strong negative and positive biases. This is because the surface smoothing presented in MERRA, due to its limited resolution (a grid point represents an area of approx. 55,3km x 74,2km). This does not properly reproduce the enhancement or weakening of the wind as a result of the flow dynamics through the topography. Furthermore, local thermal circulations such as land-see, mountain-valley breezes and the Foehn effect, which might also impact the wind resource on a site, cannot be properly determined through MERRA. To a less extent, these phenomena might also affect the cloud formation as well as the gas and aerosols transport through the topography of Colombia which might directly impact the solar irradiation in some sites.

As a consequence, the magnitude of the mean wind speeds and the solar insolation over the coastal areas in the North and West of Colombia (Atlantic and Pacific oceans respectively) are more likely to be close to the “true” value. Although a positive bias (overestimation) of 2m/s was found for the wind @80m in the Guajira site, in Colombia, with the CSFR Reanalysis in a short-period in 2012, the MERRA wind speeds found in the present study for the same site seem to be accurate: a mean wind speed of 7,5m/s @50m in a MET tower between 2007 and 2013 is very close to the 7,38m/s MERRA wind speed found for the same period.

For the areas in the valleys between the three Andes Cordilleras and over them (with several heights over 5.000m), the magnitudes of the wind and solar resource might have large biases, especially in the wind resource. These are not verified in the present study. Due to its resolution, MERRA “sees” altitudes only up to 3.000m and “sees” only one Cordillera made of two (the Western and the Central Andes). Considering only the global and regional meteorological dynamics, these biases would be positive for the wind resource mainly on the leeward of the Andes (west; because of the Trade winds are coming from the northeast and southeast) and negative (underestimation) on the windward of the Andes (east), where likely future wind projects could be located if areas with enough wind speeds are found. Nevertheless, local thermal circulation and the topography might produce stronger or weaker winds in both sides of each Cordillera. The same situation would be presented for the solar resource, due to clouds formations to one side of the Andes, and transport of gases and aerosols through the complex topography, but to a less extent.

Over- and under-estimations of MERRA on the wind and the solar resource in some areas in Colombia could be observed when compared to the data of the IRENA[1] Global Atlas map and to the *Wind and Solar Atlas of Colombia* developed by the UPME[2] and the IDEAM[3] in 2005 and 2006:

- Wind resource: There is a general similar wind resource distribution over the country of MERRA compared to the IRENA map. However a general underestimation is noticed for all the country but not for the Guajira area (northern coast, where the highest mean wind speeds were found: MERRA provides 7,66m/s @50m for the Stream 3, 2001 to 2014, IRENA provides about 8,5m/s @80m). A strong underestimation appears mainly on areas over the Eastern and Central Andes (IRENA exhibits wind speeds up to around 9m/s, where MERRA only up to 4,5-5m/s). MERRA presented higher wind over the Oriental plains, IRENA does not. No under-estimation or a slight one is presented in other areas. Compared to the UPME-IDEAM wind atlas, the wind resource distribution over the country were slightly similar but to a much less extent that the one in IRENA. Higher wind speeds were presented in the Guajira as well as in the Eastern Andes. However, high wind speeds in the Catatumbo (between the north coast and the Eastern Andes), middle of the Central Andes and north of the Western Andes are completely missed in MERRA. Furthermore, higher winds are presented in the Oriental plains in the UPME-IDEAM atlas, but more to the west, compared to MERRA. When contrasting the magnitudes the resource in the Guajira has a minor under-estimation (UPME-IDEAM presents 6-7m/s @10m). Areas over the Eastern and Central Andes and the Catatumbo region present a strong difference while having wind speeds of up to 6m/s @ 10m which are not visible in MERRA (2 – 4m/s @50m).

- Solar resource: Compared to IRENA, the general distribution of the solar resource is similar with MERRA, showing a higher resource in Andes and the Sierra Nevada de Santa Marta in the north. However MERRA displays a high resource only in one Cordillera (the Eastern). IRENA presents high resource for the three Cordilleras. For areas with a lowest resource, IRENA shows areas in the west side of the Western Andes and on the east side of the Eastern Andes. For MERRA, the lowest resource areas are located on the extreme east and on the north-northwest of the country. A slight under-estimation of MERRA compared to IRENA was found in the magnitude of the solar resource in the Oriental plains. For the remaining areas the values are quite similar. Compared to the IDEAM Solar Atlas, The distribution of

[1] International Renewable Energy Agency
[2] Mining and Energy Planning Unit of the Ministry of Mines and Energy of Colombia
[3] Institute of Hydrology, Meteorology and Environmental Studies of Colombia

the resource was surprisingly very different. IDEAM displays the highest solar resource north coastal area of the Country as well as in the Oriental plains. Some other areas on the Eastern Andes also stand out. MERRA presents similar or underestimated values outside the Andes.

The mean differences in the magnitudes are explained because the model resolution (IRENA, 5km; UPME-IDEAM 10km) which due to a lower surface smoothing, can reproduce better the resources. Furthermore, in the UPME-IDEAM atlases, on-site measurements were also included. As a result, this atlas provide a better estimates because local thermal circulations as well as enhancements or weakening of the resources in some sites are better reproduced.

The ability of MERRA of capturing time variations in the wind and the solar resource has been also awarded in several studies through the good coefficients R and R^2 (several over 0,75 in different time scales) found in many places worldwide, but not everywhere. As there is not real differences between South America and other continents, these likely good correlations are also assumed for Colombia. Nevertheless, again, this is very much site-dependent. This implies that the intra-annual and inter-annual curves of the mean monthly wind speed @50m and the mean monthly solar insolation of MERRA are likely to follow patterns of observed data. The intra-annual patterns of the monthly wind and solar resource were confirmed for most of the sites with the *Climatologic Atlas* of the IDEAM, published for some cities in 2005. The monthly river in-flows came from observed data of XM[1] on the large (>20MW) hydro power plants. Thus, there are taken as a fact. As a result, the distribution of MERRA monthly wind speeds and solar insolations are a good approximation for the calculation of correlation coefficients with monthly river in-flows, because, from the mathematical point of view, these coefficients do not depend on the magnitude of the values themselves but on the behaviour along the time. Again, the complexity of the sites and the importance of thermal mesoscale circulations together with the real topography are important to consider. Future investigations are needed for understanding this.

Although only the Stream3 of MERRA (2001-2014) was used due to time and computational constrains, slight downward trends were seen both in the annual wind and solar resources in several of the selected sites (refer to Appendices). This was confirmed in a study in the north coast of Colombia. The MERRA observational system is the likely to be the main driver for positive or negative trends in data and it has been seen in several sites of the world. Not only because of the strong increase in data in the last decades (from approx. 100.000 used in 1979 to approx. 1.500.000 in 2008 every six hours; the total inputs are much more but data filtering is applied) but also for the spatial coverage in the world. In the example presented of the radiosondes in 2008 in the Appendices, it is observed how South America and Africa might have very few observations compared with other parts of the world. This could have an impact in the data reproduced. However it is important to see that there were more observations in the

[1] Power system operator and market administrator in Colombia

Caribbean Sea (Atlantic Ocean) than for the inner parts of South America referring to the Andes and the Amazon. This support the stronger differences in the magnitudes found in the Andes compared to coastal areas in Colombia for the wind and the solar resource.

The present document did not focused on the magnitude of the wind and solar resources and their Annual Energy Production (AEP), but on the behaviour and the relationship of the resources compared with the Colombian hydrology. Nevertheless, energy calculations were executed as for providing first estimates. The approaches for calculating the energy production of wind and solar parks were confirmed with engineering online tool. However the assessments were fed with the wind and solar resource found from MERRA. As previously mentioned, the likely uncertainties of the magnitude of the wind speeds and the solar irradiations in MERRA impacts directly the Annual Energy Productions (AEP) found. And thus, they are only rough estimates, must be addressed carefully and should not be used for commercial purposes without further analysis. This affects much more the AEPs of the wind parks than of the solar parks because of the higher sensitivity resource-to-energy relationship. Based on the under- and overestimations found compared to IRENA and the UPME-IDEAM wind and solar atlases: the AEPs presented for the selected wind parks in the Andes are likely to be strong underestimated. The ones for the coast might be much closer to the reality. On the contrary, the AEPs presented for the selected solar parks in the Andes might be slight overestimated. Again, the ones for the coast might be much closer to the reality. In the case of the hydroelectric energy, the approach for assessing it gave similar AEPs compared to real generation data from XM. However, when plotting an example of the monthly generation of a hydro power plant, a very different pattern was observed. This might be due to the influence of power plants with large water reservoirs and due to operational procedures based on market strategies, which are out of the scope of this study. This non correlation on a monthly basis has been seen in other studies. As a result, the energy assessment was done as described (directly with the river in-flows in the conversion factor made available by XM) because it represents better the real condition of the hydrology of the country, of important in the complementarity results not only for dam hydro power plants but also for run-of-the-river hydro power plants all over Colombia.

For the intra-annual patterns, it was concluded that global meteorological dynamic called ITCZ[1] along with the Trade winds are the main drivers of the intra-annual patterns of the found wind and solar resource in Colombia. When the ITCZ is on its extreme south, it is more distant to northern regions of Colombia generating stronger winds in the north. Furthermore, more clouds and precipitations are expected in the south. On the contrary, when the ITCZ is on its extreme north, it is more distant to the south of Colombia producing stronger winds in the south. Moreover, more clouds and precipitations are expected in the north. The regions in between, observe the ITCZ twice during the year. Although the ITCZ might also explain the precipitation patterns in Colombia, it cannot easily explain the intra-annual behaviours of the river in-flows. This, because of the time-delayed formation of river in-flows given by complex

[1] Inter-Tropical Converge Zone

hydrology dynamics comprising the topography the river follows, types of soils, underground waters, underground reservoirs, evaporation, among others. These hydrology dynamics are out of the scope of this study and thus, the intra-annual river in-flows of XM were taken as a fact because they come from observations on the hydro power plants.

The mean intra-annual complementarities between the wind resource and the hydro resource and between the solar resource and the hydro resource were presented. Interestingly, although there is a wide variety of positive, negative and non- correlations countrywide[1], the largest group of negative correlation coefficients (R > 0,5; indicating strong complementarity) were mostly found for both the wind and solar resource in the following combinations:

- River in-flows in the north (Central Andes) with wind speeds/solar insolations in the north (Caribbean coast/Central Andes)
- River in-flows in the south (Western Andes) with wind speeds/solar insolations in the south/centre (Eastern Andes)

As a consequence, future wind and solar parks located close to the selected wind/solar sites in the presents study, might be able to backup hydro power plants in the regions nearby[2] in months where these regions have critical low hydrology, entailing a very important advantage in in terms of energy transport in the transmission system.

For the inter-annual complementaries between 2001 and 2014, the results are not as limited to some areas as for the intra-annual ones. Nevertheless,, the largest group of negative correlation coefficients (R > 0,5) were mostly found between

- River in-flows of the north (Central Andes) with wind speeds of all areas of the Eastern Andes
- River in-flows of the north/centre (Eastern Andes) with solar insolations of the south/centre of the (Eastern Andes)

For inter-annual complementarities, the sites found were not located nearby. However, these could provide a general backup for the country in years with low hydrology as it was observed in this study for the years 2001-2002, where a los hydrology period would have been compensated by high wind and solar resources over the country.

Although the complementarity of renewable resources in different time and space scales are still not valued Colombian energy market, further studies in the topic should be implemented as to clearly propose market strategies such as Complementary Charges for generators with

[1] the readers are hereby highly encouraged to check the tables by themselves
[2] This refers to a physical distance of some hundreds of km between the hydro power plants and the wind/solar sites selected in this study. However, it presents a “nearby” in terms of energy transmission traffic in the south, centre and north of the country

mixed generation matrixes. Having in mind the capacity of hydro power plants with reservoirs of balancing systems with high fluctuations, this would encourage the development of power plants based on wind and solar resources.

The Inter-Annual Variabilities (IAV) found were in accordance to the studies found. In the area of the ITCZ, where Colombia is located, higher IAVs where expected as in subtropical areas. For the annual wind speeds, IAVs between 2,9 and 8,5% were found for the period 2001-2014. For the annual solar insolation, IAVs of 2 to 6,2% were obtained. This shows the higher variability of the wind compared to the solar resource. In the case of the hydro resource, and likely due to weather phenomena not studies in detailed here, such as the ENSO, strong IAVs of up to 43,7% were found, depicting the vulnerability of a generation matrix based mostly in hydro power as the Colombian one.

9 Future works recommended

Based on multi-lateral agreements between the UPME, IDEAM, state generators, private generators, transmission companies, XM, Banks and Universities (and their counterparts in other countries), the following steps should be executed in the future:

- Validation of MERRA wind and solar data with meteorological stations over Colombia as to evaluate the accuracy in magnitude and as to execute proper de-trending of data. While developing this study, it was known that the IDEAM would easily provide this information. It is encourage to make the first validations in areas of the Andes because the uncertainties are likely to be larger there. In the northern coastal areas, Guajira, this study confirmed a good accuracy in the magnitude and behaviour of the wind speed with MERRA.

- Aiming the same of the previous bullet point, mesoscale modelling of the wind and solar resources in sites with the highest mean values and with the highest intra- and inter-annual complementarities should be done. An example of these models is WRF (Weather Research and Forecasting)

- Analysis of the meteorological development of the river in-flows over Colombia as to further understand where and when the wind resource and the solar resource are complementary on an intra- or inter-annual time scale.

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11 Appendices

11.1 Available global Reanalyses

Product			Source		Time span			Temporal resolution	Horizontal spatial resolution				Vertical levels		Format	Scheme and model vintage
Abbreviation	Name	Type	Abbreviation	Origin	From	To	Years	[Hours]	Latitude [°]	Longitude [°]	Latitude [km] in Equator	Longitude [km] in Equator	Top [hPA]	Levels		
CFSR	Climate Forecast System Reanalysis	First coupled atmosphere-ocean	NCEP	USA	1979	2010	31	6	0,5	0,5	55,3	55,7	0,266	64	GRIB	3DVAR/2009
ERA Interim		Atmosphere	ECMWF	Europe	1979	Present	35	12 for analysis. 3 for most surface fields. 6 for upper-air fields.	0,75	0,75	82,9	83,5	0,1	60	netCDF, GRIB	4DVAR/2006
MERRA	Modern Era Retrospecive analysis for Research and Applications	Atmosphere	NASA	USA	1979	Present	35	1 for 2D Diagnostics. 3 for 3D Diagnostics. 6 for 3D Analysis	0,5	0,67	55,3	74,2	0,1	72 model levels and 42 pressure levels	netCDF, HDF	3DVAR. Incremental Analysis Updates (IAU). GEOS/2009
JRA-55	Japanese 55-year Reanalysis	Atmosphere	JMA	Japan	1958	2012	54	6. Partly 3	1,25	1,25	138,2	139,2	0,1	40	GRIB	4DVAR/2009

Table 38: Main characteristics of the *third generation* Reanalyses

11.2 Mean values of the retrieved variables of Stream 3 of MERRA

Mean wind speed @ 50m and surface air density

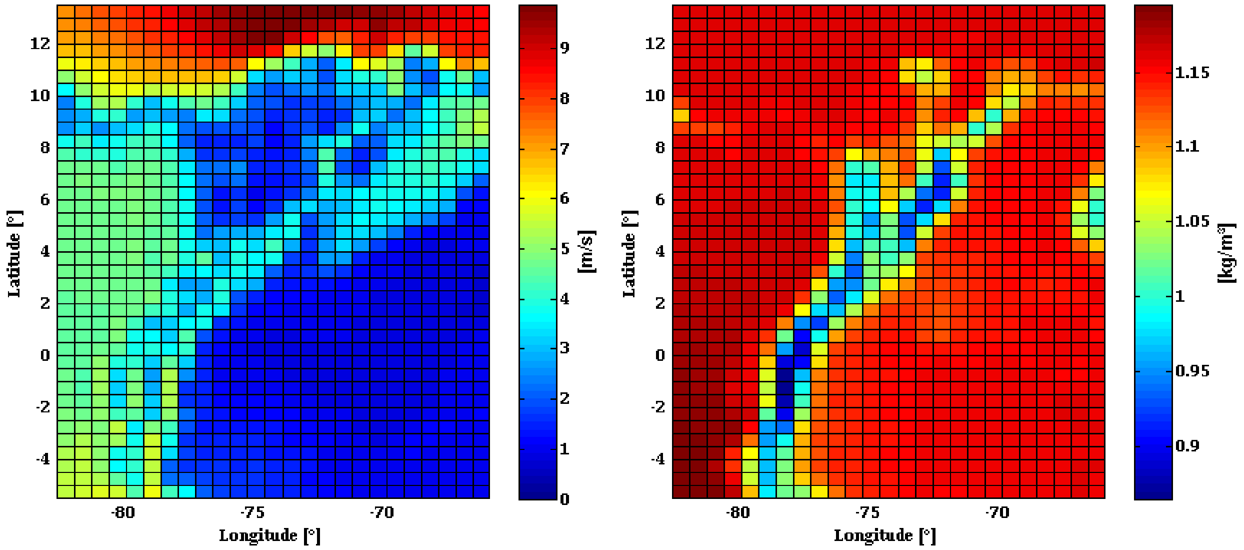


Figure 37: (left) Mean values of wind speed @ 50m in [m/s] and (right) mean surface air density in [kg/m^3] from 2001 to 2014

Mean annual surface solar insolation and temperature at 2 m

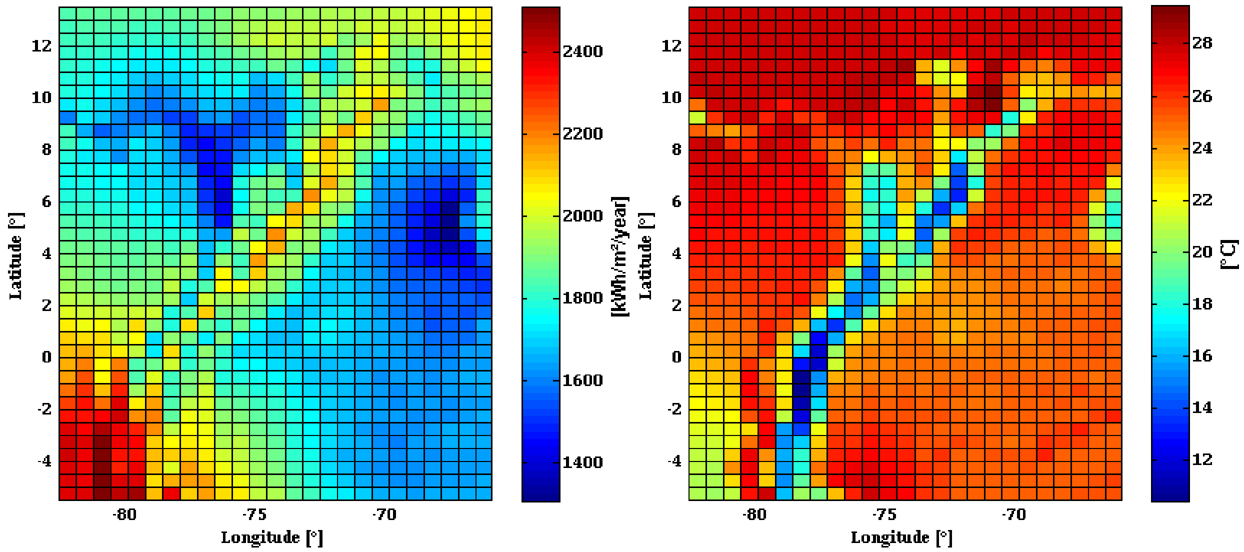


Figure 38: (left) Mean values of annual surface solar insolation in [kWh/m^2/year] and (right) mean temperature[1] at 2 m above displacement height in [°C] from 2001 to 2014

[1] All temperatures counted, both during the day and during the night

Mean total surface precipitation and overland runoff

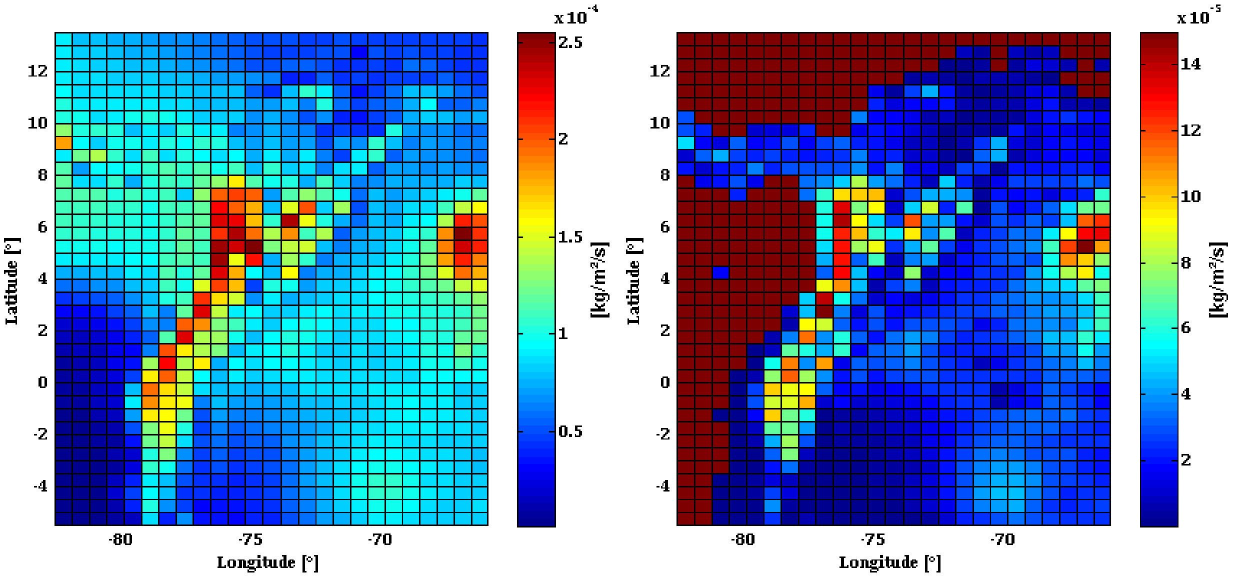


Figure 39: (left) Mean total surface precipitation in [kg/m^2/s] and (right) mean overland runoff in [kg/m^2/s] from 2001 to 2014

Mean roughness length and displacement height

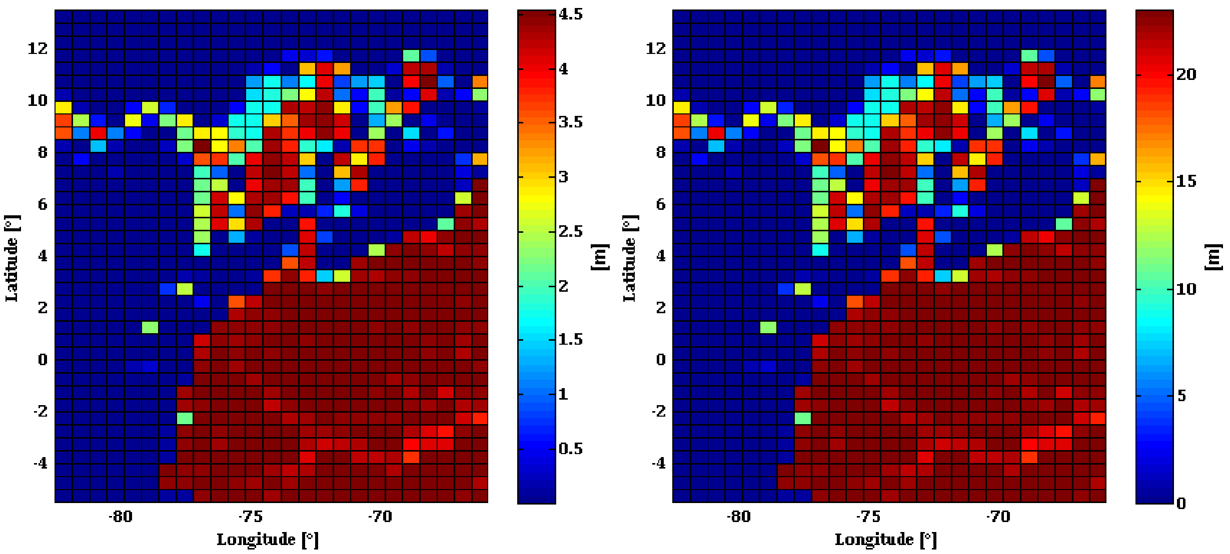


Figure 40: (left) Mean roughness length in [m] and (right) mean displacement height in [m] from 2001 to 2014

11.3 Roughness lengths classification

Roughness length z_0	Land cover types
0.0002 m	Water surfaces: seas and Lakes
0.0024 m	Open terrain with smooth surface, e.g. concrete, airport runways, mown grass etc.
0.03 m	Open agricultural land without fences and hedges; maybe some far apart buildings and very gentle hills
0.055 m	Agricultural land with a few buildings and 8 m high hedges seperated by more than 1 km
0.1 m	Agricultural land with a few buildings and 8 m high hedges seperated by approx. 500 m
0.2 m	Agricultural land with many trees, bushes and plants, or 8 m high hedges seperated by approx. 250 m
0.4 m	Towns, villages, agricultural land with many or high hedges, forests and very rough and uneven terrain
0.6 m	Large towns with high buildings
1.6 m	Large cities with high buildings and skyscrapers

Table 39: Roughness lengths classification [96]

11.4 Height above see level of each of the MERRA grid points

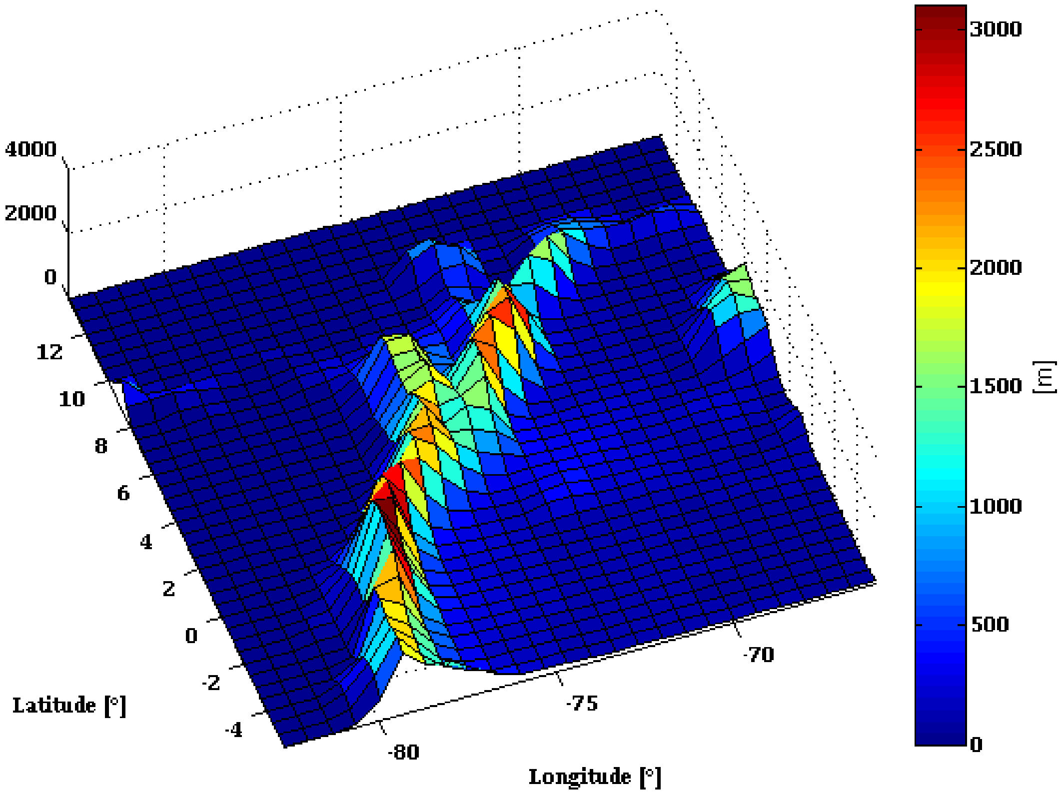


Figure 41: Constant values of height above see level of each of the grid points

11.5 MERRA input data

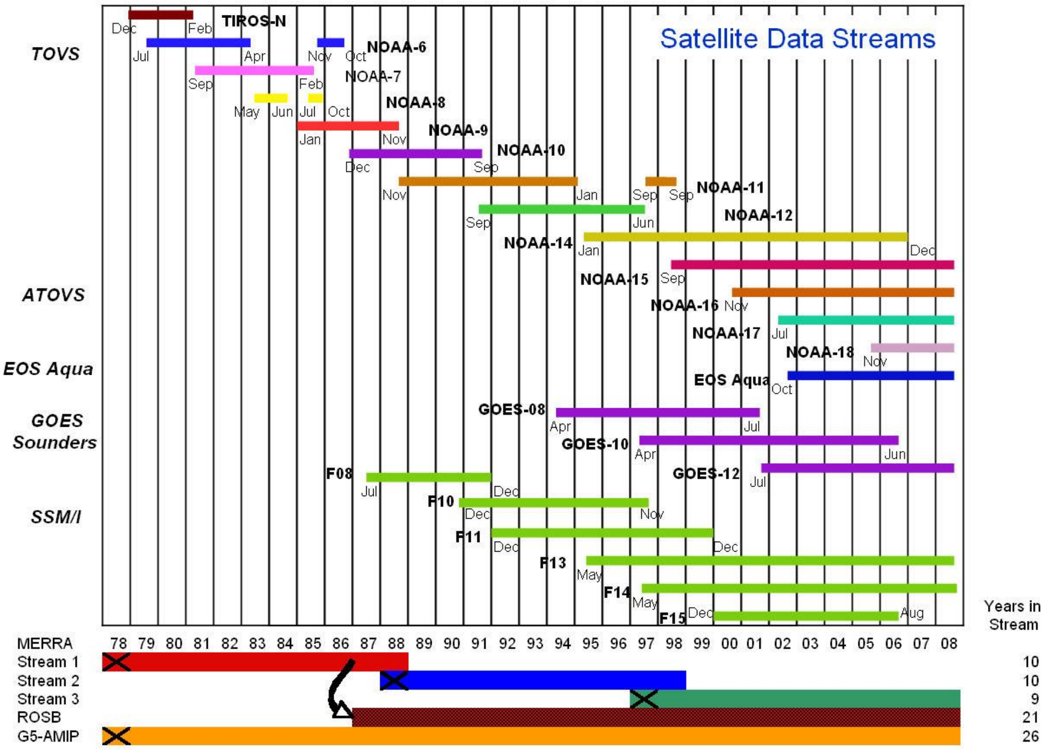


Figure 42: Satellite data stream used in MERRA through the years. Taken from [31]

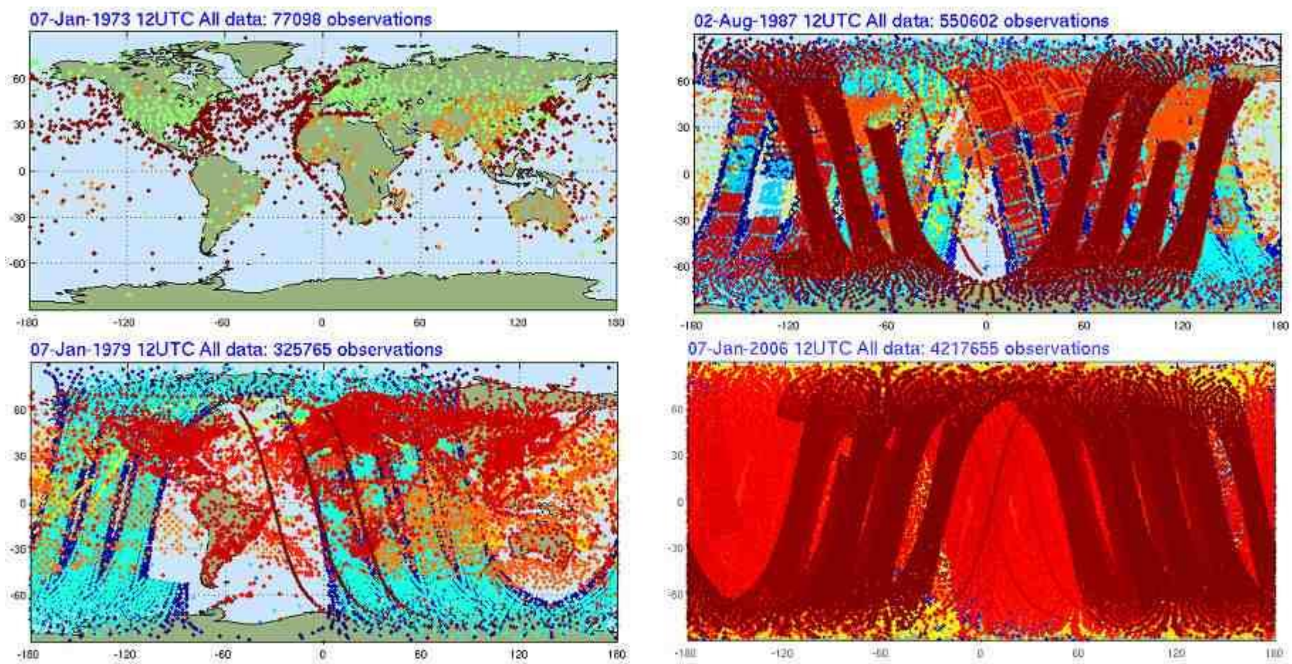


Figure 43: Observing systems from 1973 (pre-satellite) to 1979 (TIROS Operational Vertical Sounder {TOVS}) to 1987 (add Special Sensor Microwave Imager {SSMI} and several TOVS) to 2006 (add Atmospheric Infrared Sounder {AIRS} and several each of TOVS and SSMI). Taken from [97]

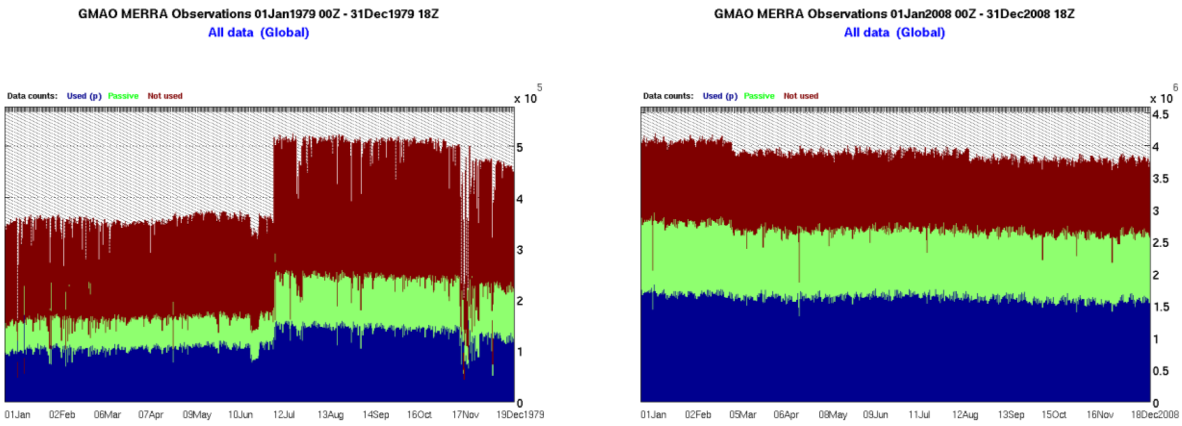


Figure 44: Observations used (blue) and not used (red) by MERRA in (Left) 1979 and (Right) 2008 every six hours. Please note the scale of the graphs: in 1979 it is x10^5, in 2008 t is x10^6. Taken from [98]

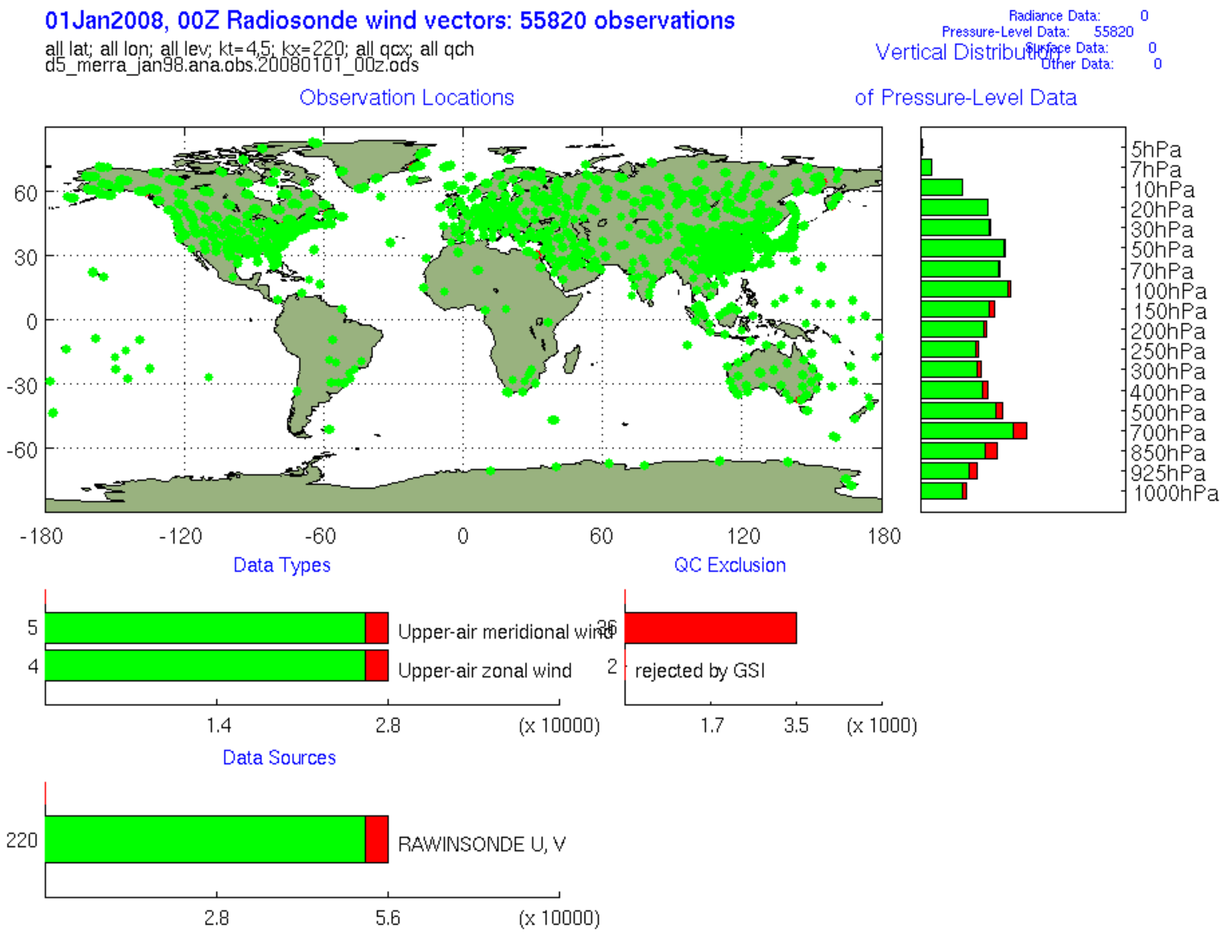


Figure 45: Radiosondes measuring wind at 00:00GTM on the 1st of January of 2008. Taken from [98]

11.6 Monthly wind speeds @ 50m and energy production at the 13 wind sites[1,2]

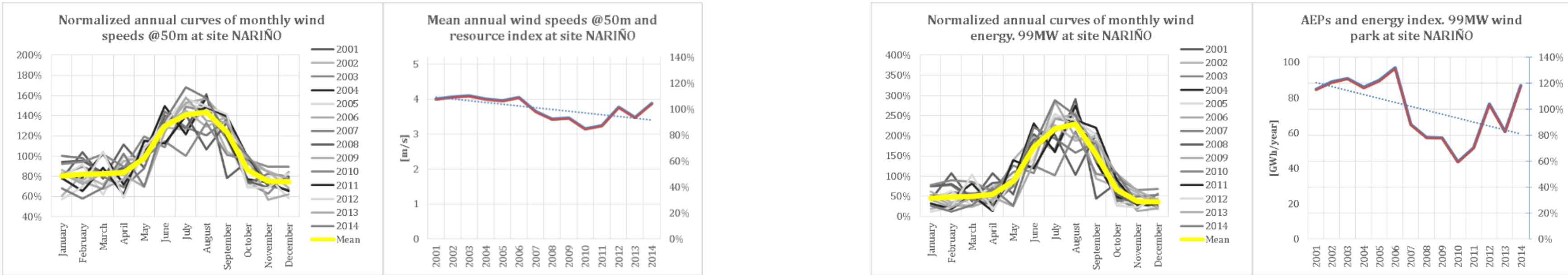


Figure 46: (Left) Wind speeds @ 50m at wind site 1, Nariño, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 3,73m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 74,04GWh/year

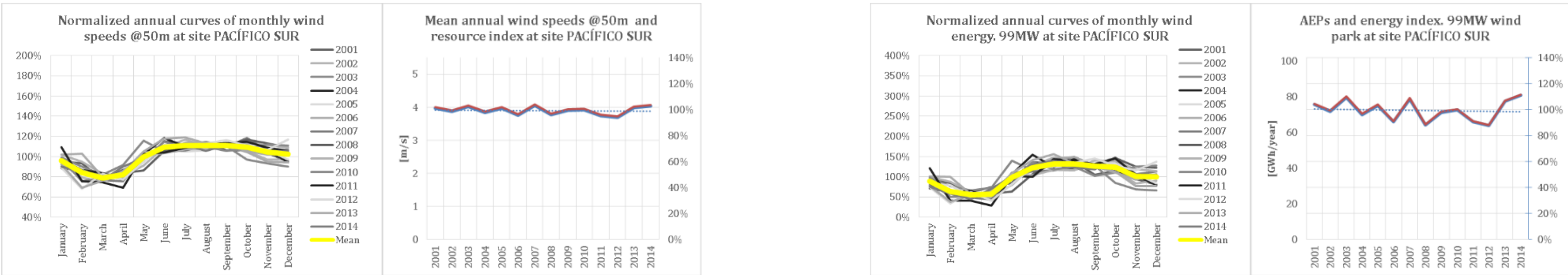


Figure 47: (Left) Wind speeds @ 50m at wind site 2, Pacífico Sur, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 3,90m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 72,46GWh/year

1 For every year, the normalized curve was calculated with the average of its year. The "100%" value in the caption corresponds to the average of all the 14 years of the Stream 3 of MERRA (2001-2014), both for the mean wind speed @50m and for the AEP of the simulated wind park
2 Reminder: the numbering of the sites was chosen based on their locations within Colombia from South to North

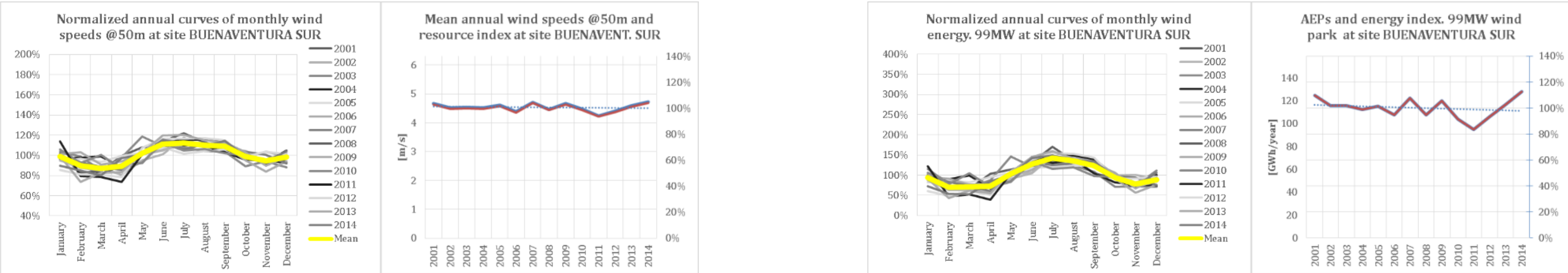


Figure 48: (Left) Wind speeds @ 50m at wind site 3, Buenaventura Sur, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 4,53m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 113,62GWh/year

Figure 49: (Left) Wind speeds @ 50m at wind site 4, Tolima, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 3,58m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 52,04GWh/year

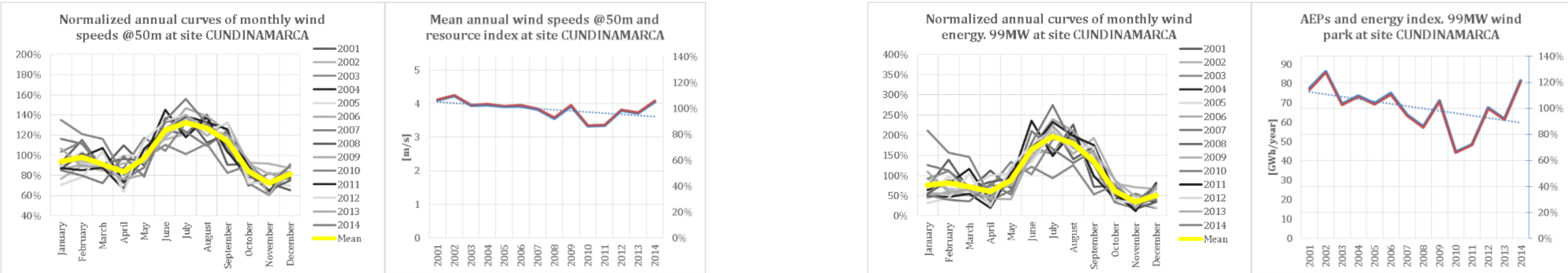


Figure 50: (Left) Wind speeds @ 50m at wind site 5, Cundinamarca, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 3,83m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 67,67GWh/year

Figure 51: (Left) Wind speeds @ 50m at wind site 6, Casanare, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 3,34m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 62,22GWh/year

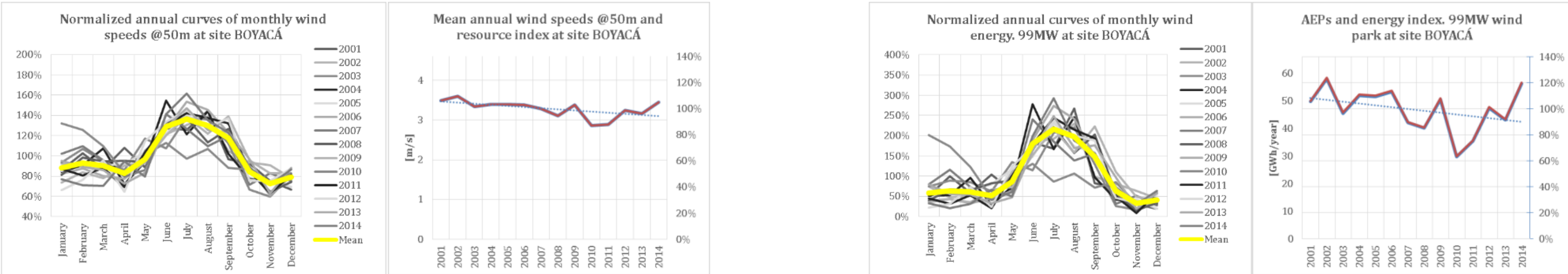


Figure 52: (Left) Wind speeds @ 50m at wind site 7, Boyacá, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 3,29m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 46,79GWh/year

Figure 53: (Left) Wind speeds @ 50m at wind site 8, Arauca, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 3,43m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 68,10GWh/year

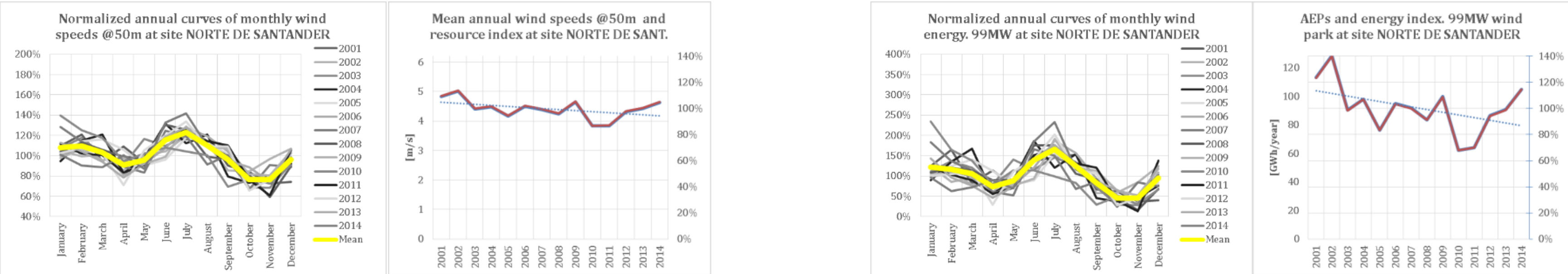


Figure 54: (Left) Wind speeds @ 50m at wind site 9, Norte de Santander, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 4,41m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 91,69GWh/year

Figure 55: (Left) Wind speeds @ 50m at wind site 10, Córdoba, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 3,31m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 70,73GWh/year

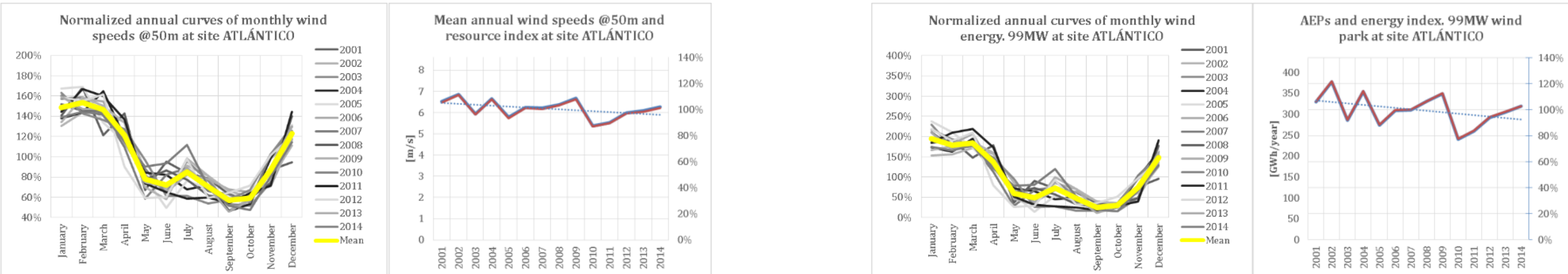


Figure 56: (Left) Wind speeds @ 50m at wind site 11, Atlántico, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 6,18m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 309,88GWh/year

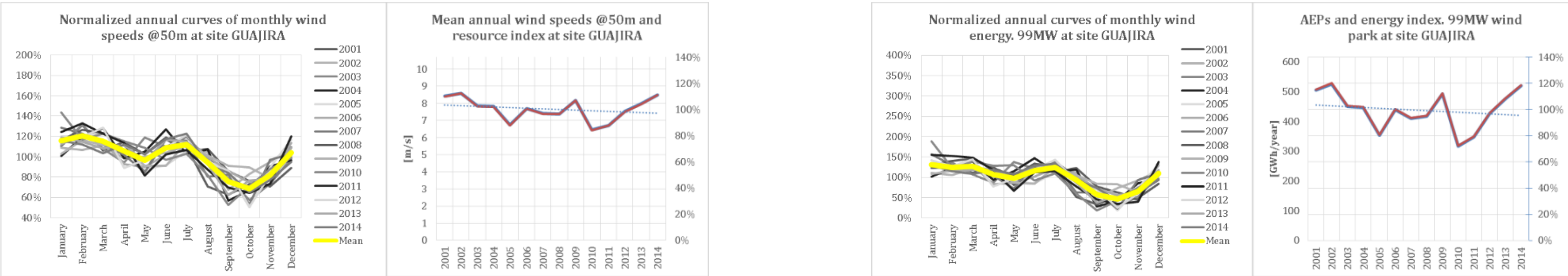


Figure 57: (Left) Wind speeds @ 50m at wind site 12, Guajira, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 7,66m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 437,21GWh/year

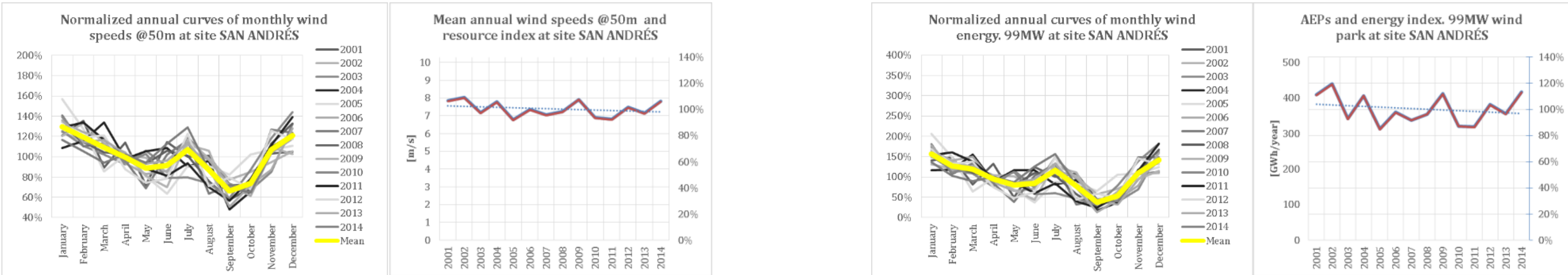


Figure 58: (Left) Wind speeds @ 50m at wind site 13, San Andrés, and its MERRA-based wind resource index. Annual mean wind speed (100% of yellow line) equals to 7,38m/s. (Right) Wind energy of a 99MW wind park at the same site and its MERRA-based wind energy index. Annual AEP (100% of yellow line) equals to 369,14GWh/year

11.7 Monthly surface solar insolation and energy production at the 14 solar sites[1][2]

Figure 59: (Left) Solar insolation at solar site 1, Nariño Sur, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 2.082kWh/m²/year (or 5,70kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 78,94GWh/year

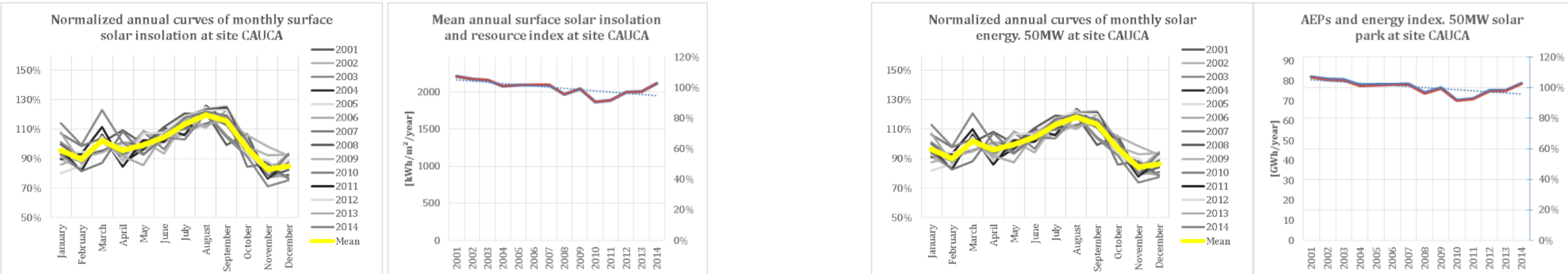
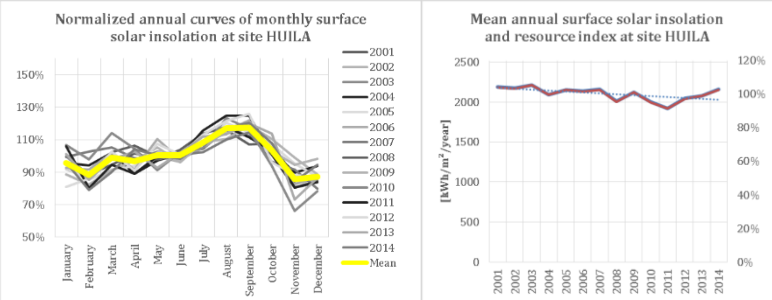


Figure 60: (Left) Solar insolation at solar site 2, Cauca, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 2.057kWh/m²/year (or 5,64kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 77,04GWh/year

[1] For every year, the normalized curve was calculated with the average of its year. The "100%" value in the caption corresponds to the average of all the 14 years of the Stream 3 of MERRA (2001-2014), both for the mean solar surface insolation and for the AEP of the simulated solar park

[2] Reminder: the numbering of the sites was chosen based on their locations within Colombia from South to North



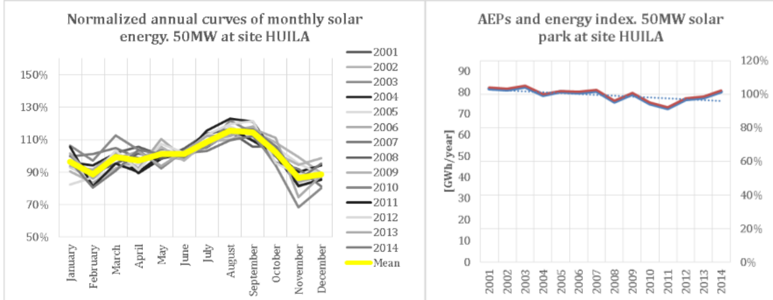
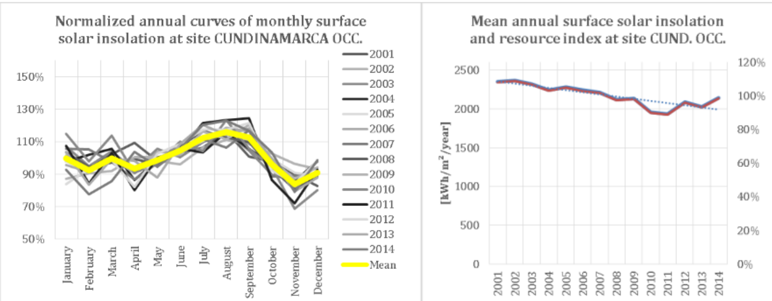


Figure 61: (Left) Solar insolation at solar site 3, Huila, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 2.105kWh/m²/year (or 5,77kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 78,63GWh/year



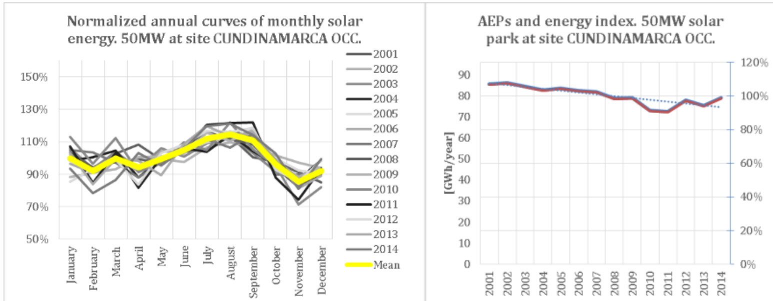


Figure 62: (Left) Solar insolation at solar site 4, Cundinamarca Occidente, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 2.175kWh/m²/year (or 5,96kWh/m²/day).(Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 80,30GWh/year

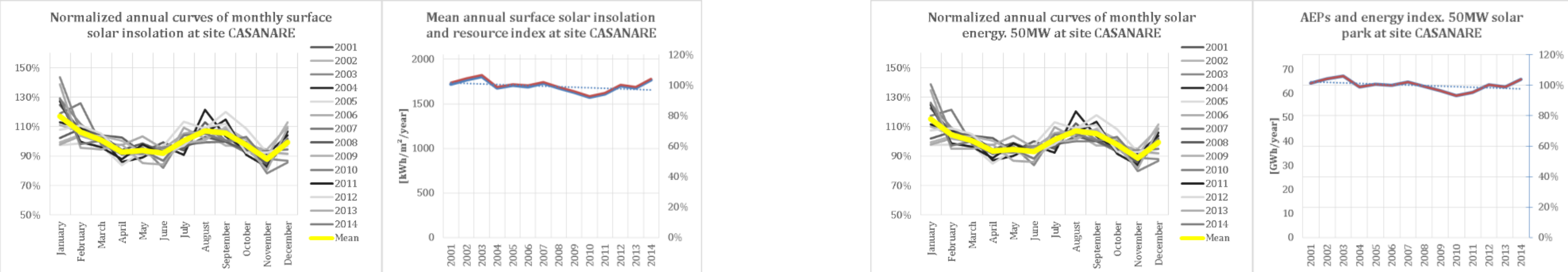


Figure 63: (Left) Solar insolation at solar site 5, Casanare, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 1.695kWh/m²/year (or 4,64kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 63,33GWh/year

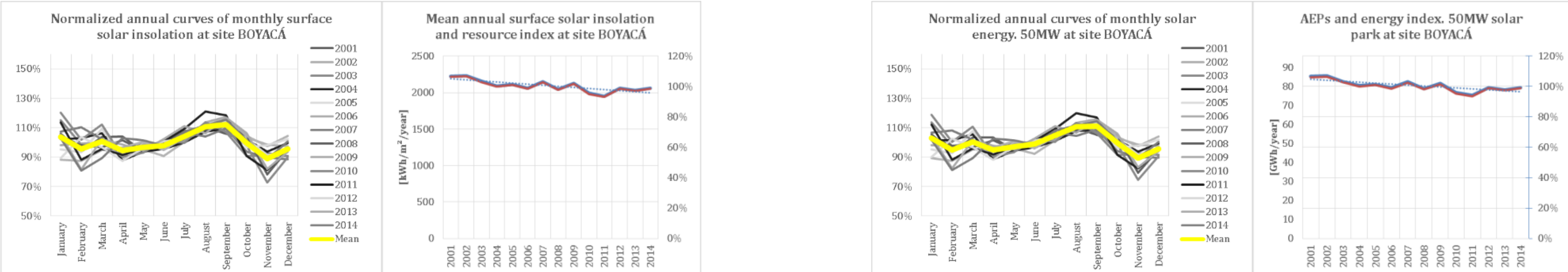


Figure 64: (Left) Solar insolation at solar site 6, Boyacá, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 2.092kWh/m²/year (or 5,73kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 80,50GWh/year

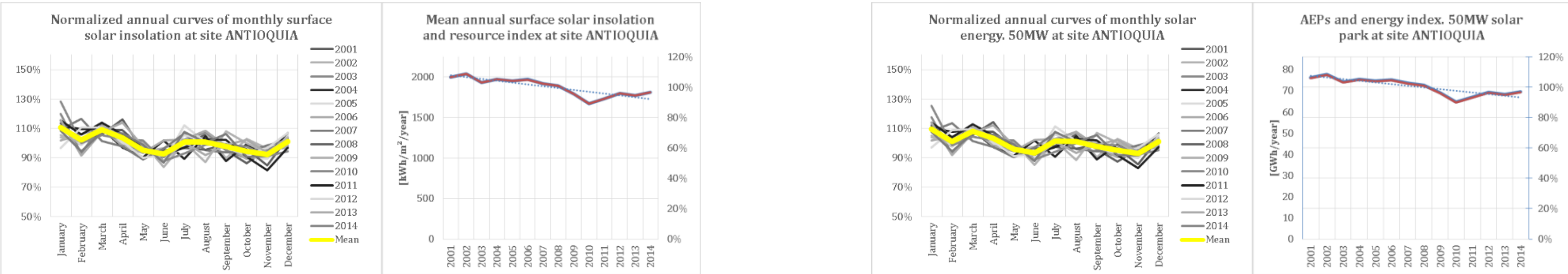


Figure 65: (Left) Solar insolation at solar site 7, Antioquia, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 1.875kWh/m²/year (or 5,14kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 71,93GWh/year

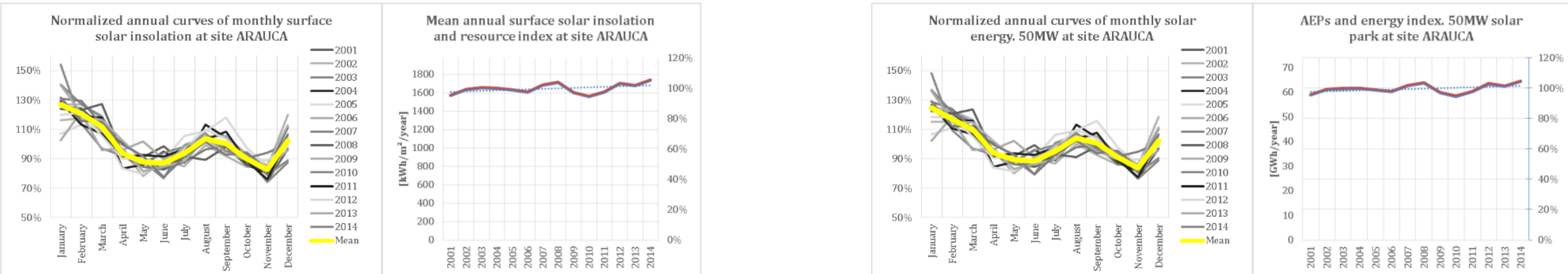


Figure 66: (Left) Solar insolation at solar site 8, Arauca, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 1.645kWh/m²/year (or 4,51kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 61,38GWh/year

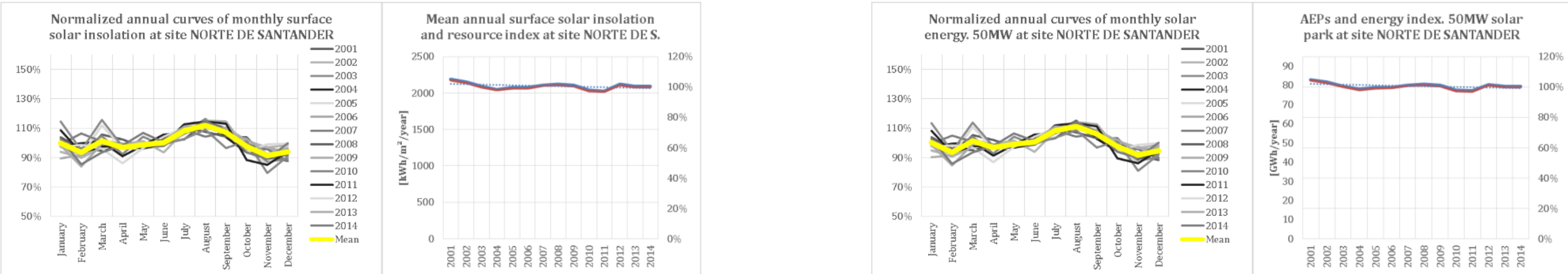


Figure 67: (Left) Solar insolation at solar site 9, Norte de Santander, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 2.096kWh/m²/year (or 5,74kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 79,59GWh/year

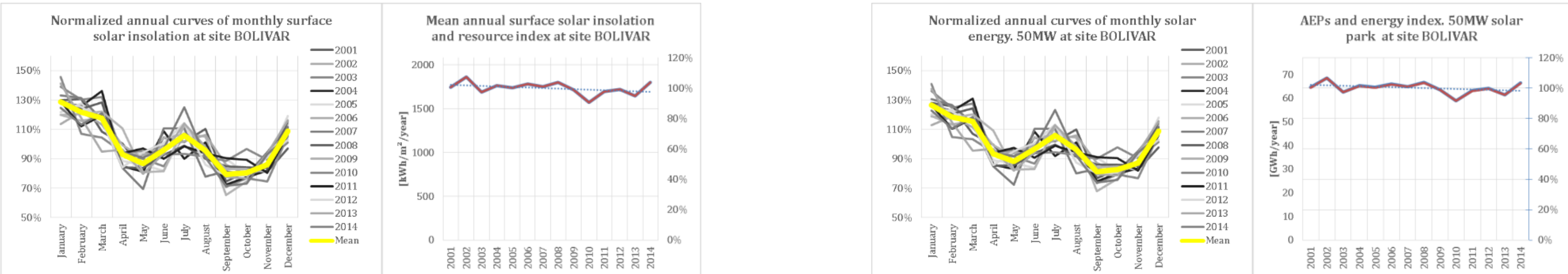


Figure 68: (Left) Solar insolation at solar site 10, Bolivar, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 1.733kWh/m²/year (or 4,75kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 64,28GWh/year

Figure 69: (Left) Solar insolation at solar site 11, Cesar, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 1.939kWh/m²/year (or 5,31kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 71,73GWh/year

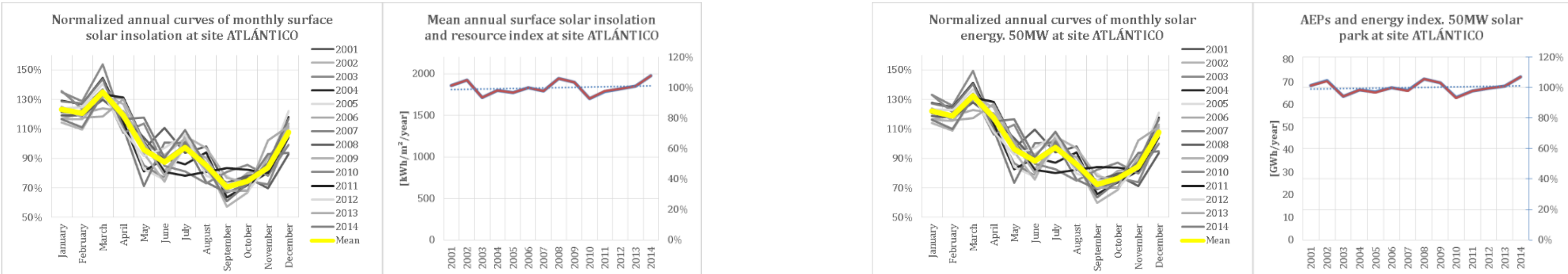


Figure 70: (Left) Solar insolation at solar site 12, Atlántico, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 1.833kWh/m²/year (or 5,02kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 64,55GWh/year

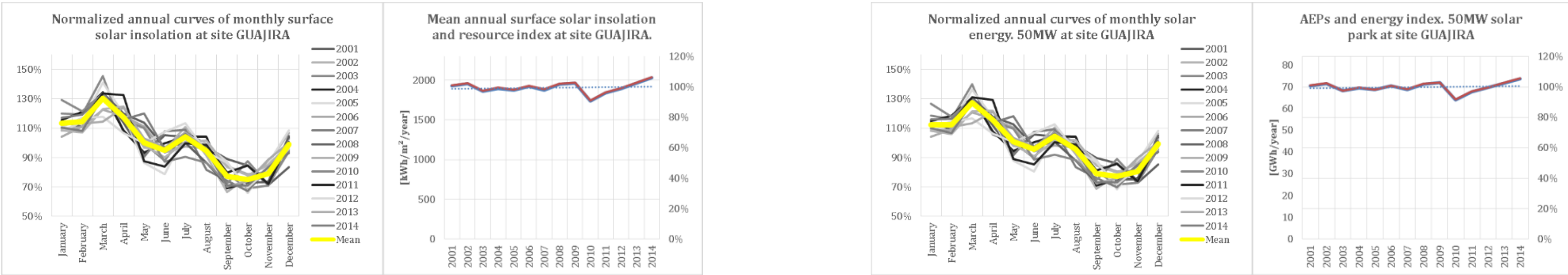


Figure 71: (Left) Solar insolation at solar site 13, Guajira, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 1.908kWh/m²/year (or 5,23kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 69,86GWh/year

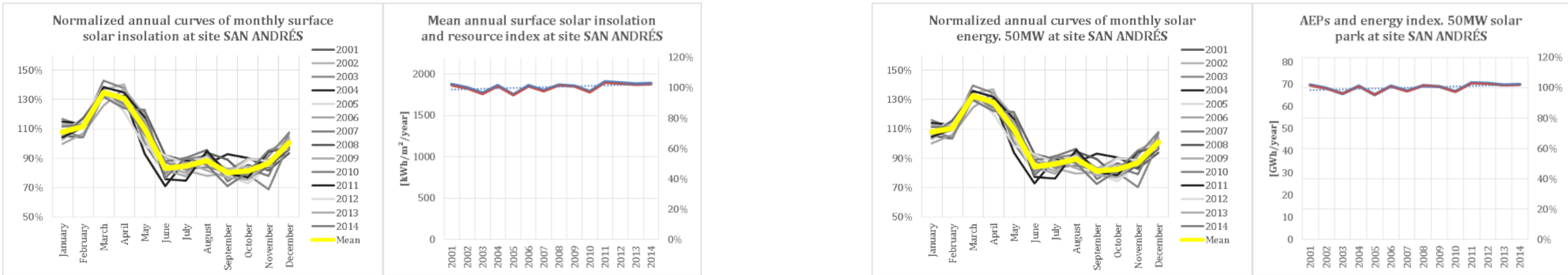


Figure 72: (Left) Solar insolation at solar site 14, San Andrés, and its MERRA-based solar resource index. Annual mean insolation (100% of yellow line) equals to 1.845kWh/m²/year (or 5,05kWh/m²/day). (Right) Solar energy of a 50MW solar park at the same site and its MERRA-based solar energy index. Annual AEP (100% of yellow line) equals to 68,52GWh/year

11.8 Monthly in-flows of the aggregated National group and the 24 rivers[1,2]

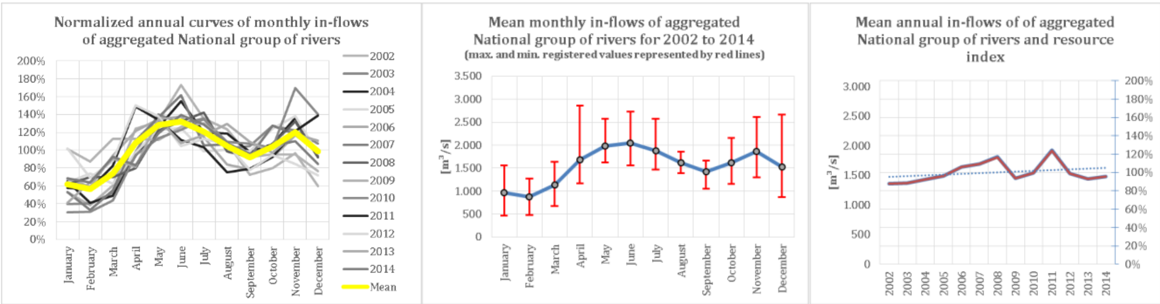


Figure 73: In-flows of aggregated National group and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 1550,80 m^3/s

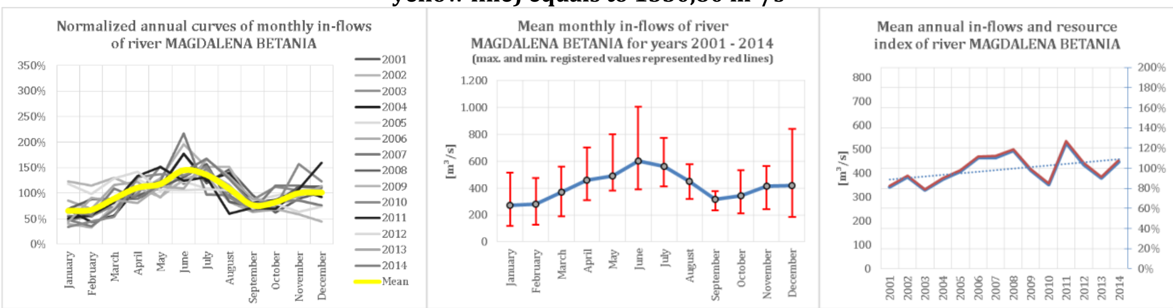


Figure 74: In-flows of river Magdalena Betania and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 414,58 m^3/s

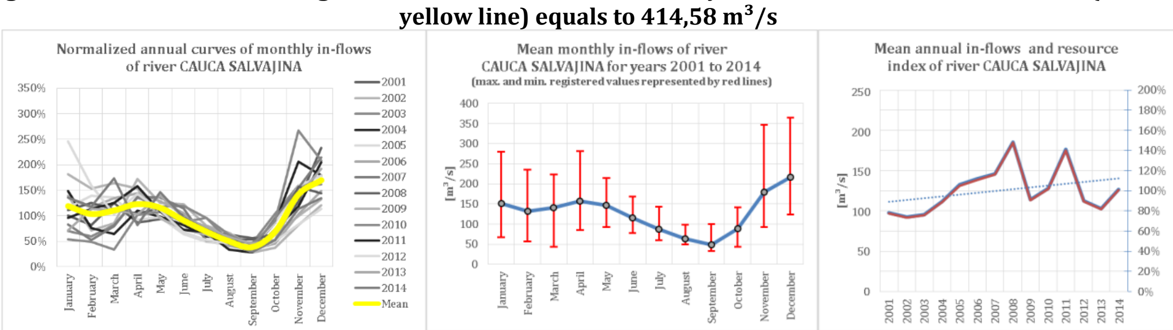


Figure 75: In-flows of river Cauca Salvajina and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 127,40 m^3/s

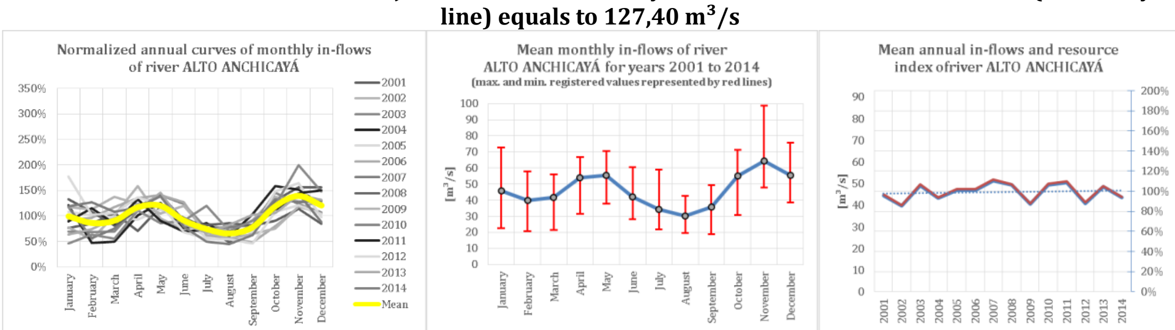


Figure 76: In-flows of river Alto Anchicayá and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 46,10 m^3/s

[1] For every year, the normalized curve was calculated with the average of its year. The “100%” value in the caption corresponds to the average of all the 14 years obtained from XM (2001-2014)

[2] Reminder: the rivers are presented based on their locations within Colombia from South to North

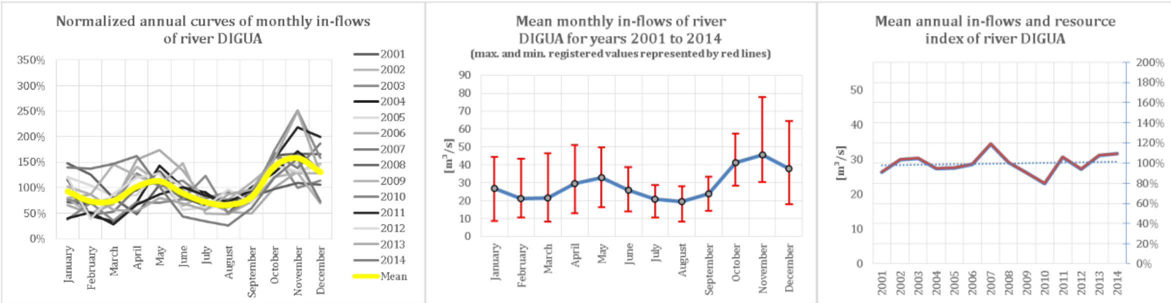


Figure 77: In-flows of river Digua and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 28,86 m^3/s

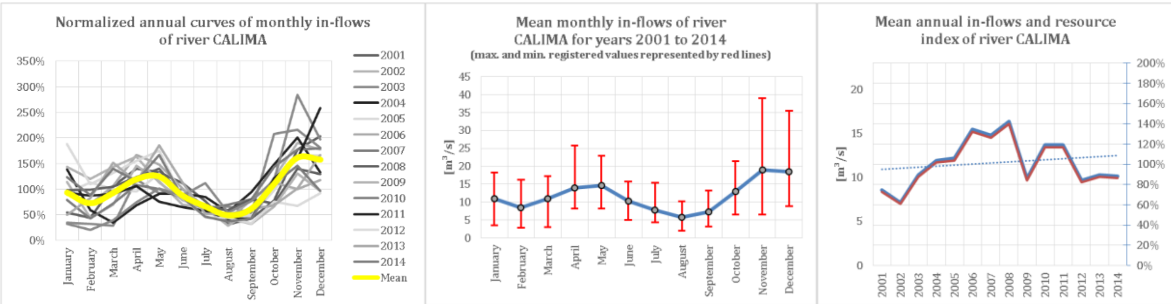


Figure 78: In-flows of river Calima and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 11,71 m^3/s

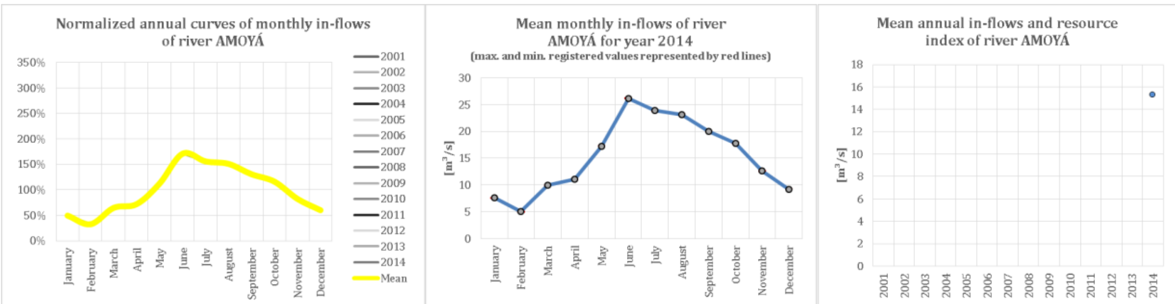


Figure 79: In-flows of river Amoyá and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 15,32 m^3/s

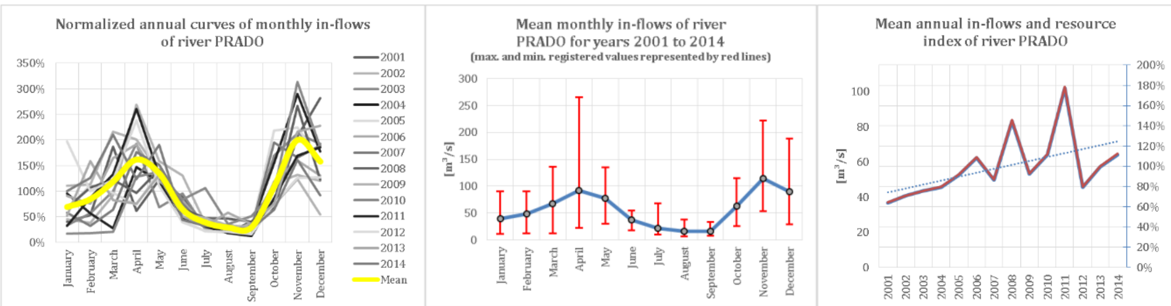


Figure 80: In-flows of river Prado and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 57,13 m^3/s

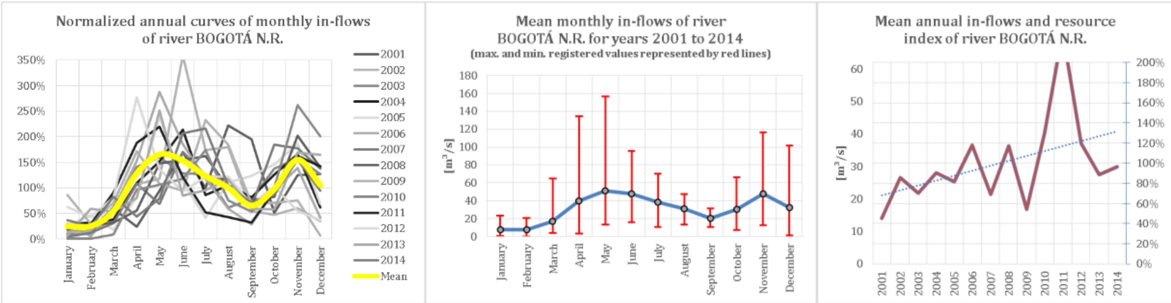


Figure 81: In-flows of river Bogotá N.R. and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 30,94 m³/s

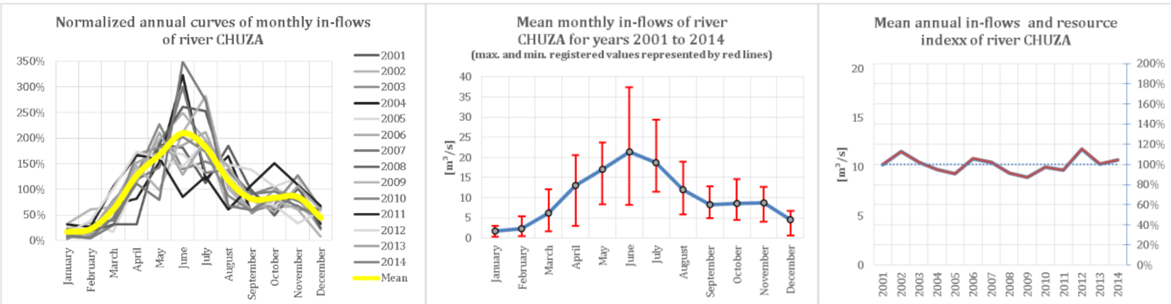


Figure 82: In-flows of river Chuza and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 10,23 m³/s

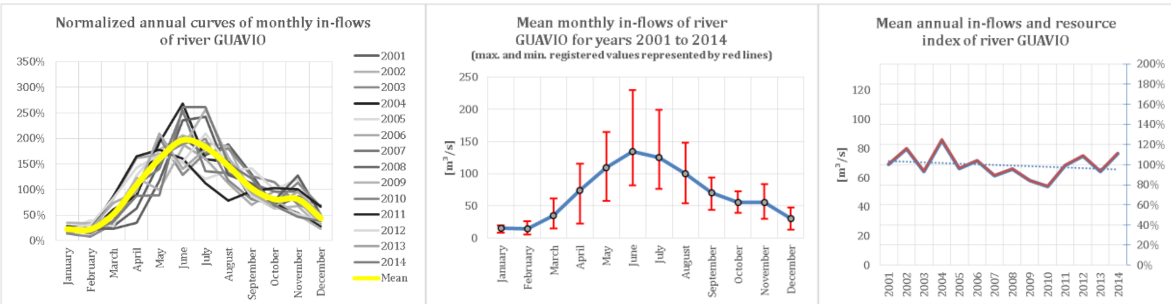


Figure 83: In-flows of river Guavio and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 68,57 m³/s

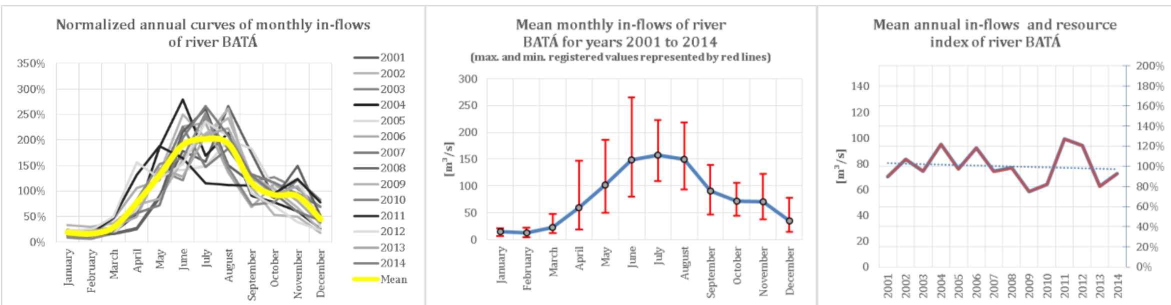


Figure 84: In-flows of river Batá and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 78,10 m³/s

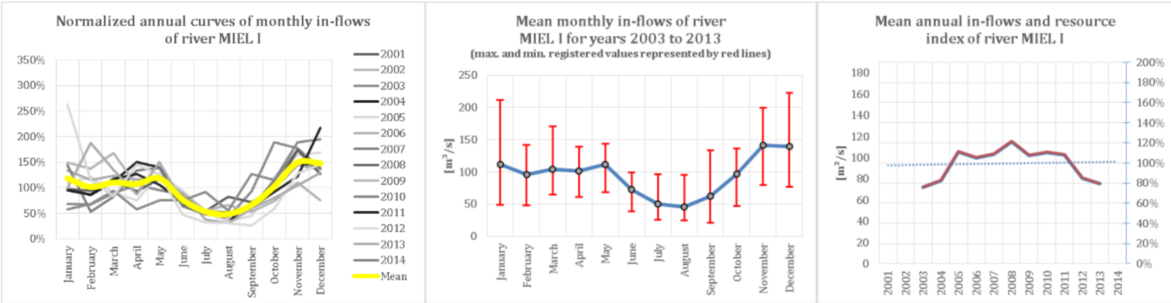


Figure 85: In-flows of river Miel I and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 94,51 m^3/s

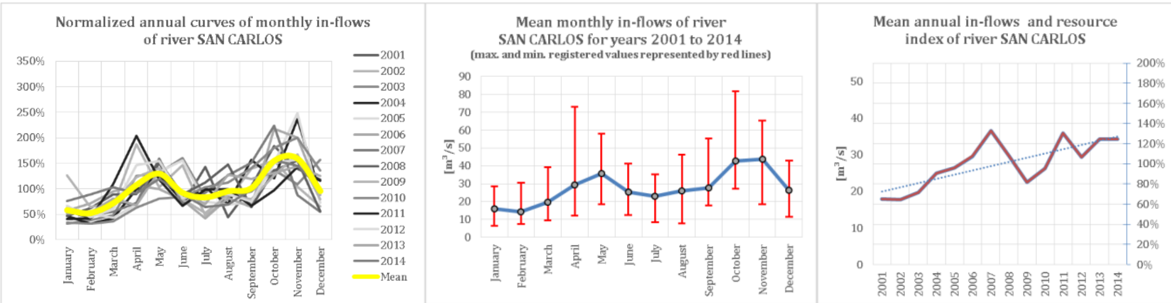


Figure 86: In-flows of river San Carlos and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 27,48 m^3/s

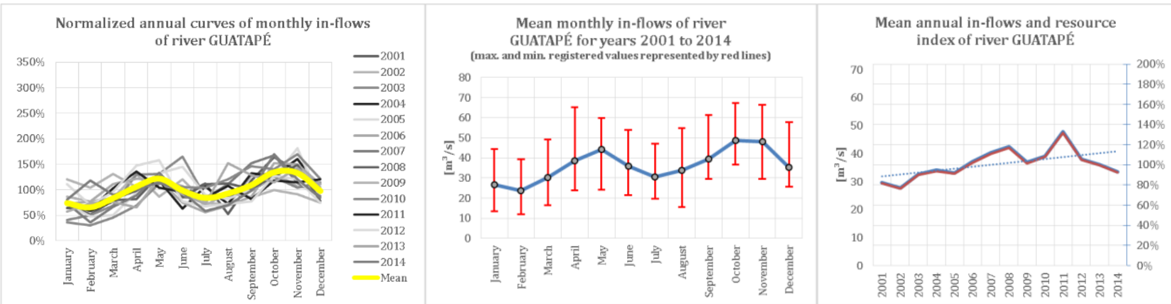


Figure 87: In-flows of river Guatapé and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 36,31 m^3/s

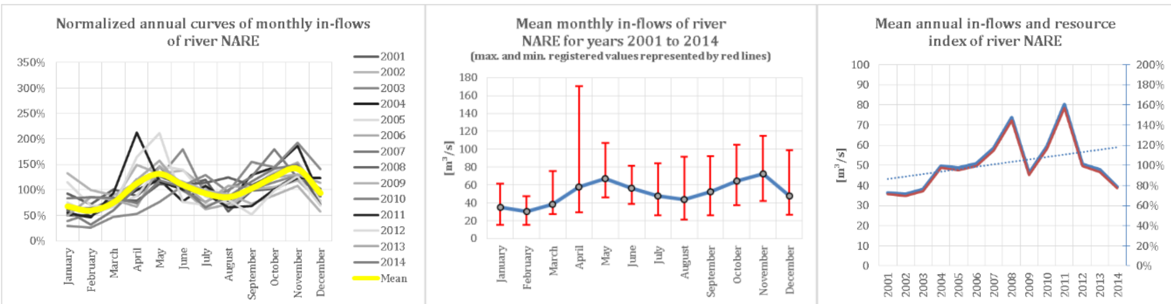


Figure 88: In-flows of river Nare and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 51,08 m^3/s

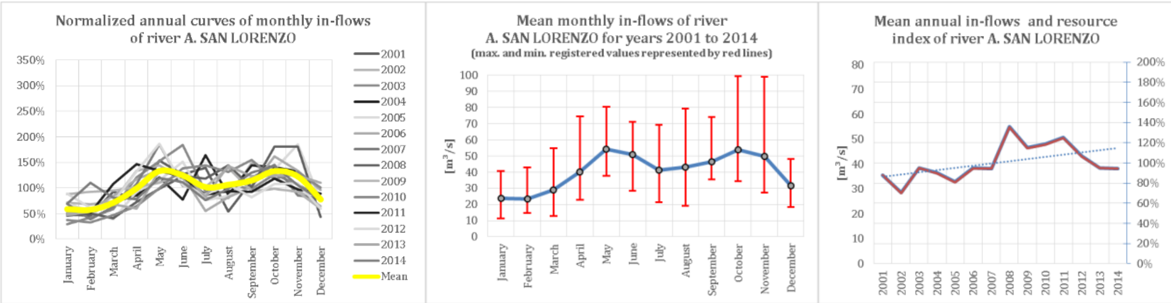


Figure 89: In-flows of river A. San Lorenzo and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 40,65 m^3/s

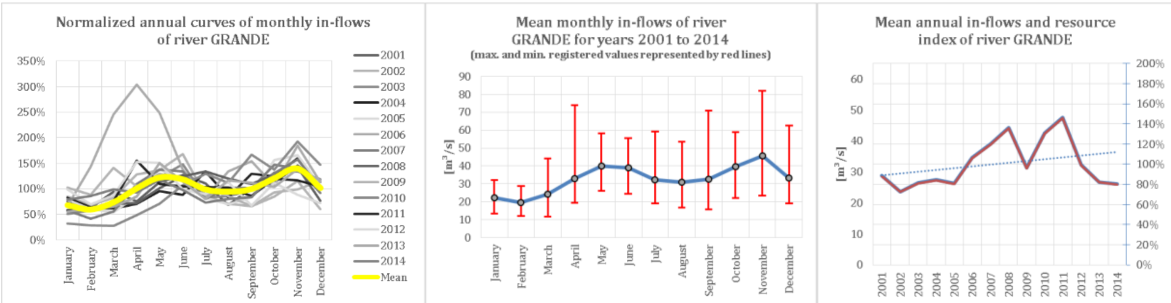


Figure 90: In-flows of river Grande and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 32,70 m^3/s

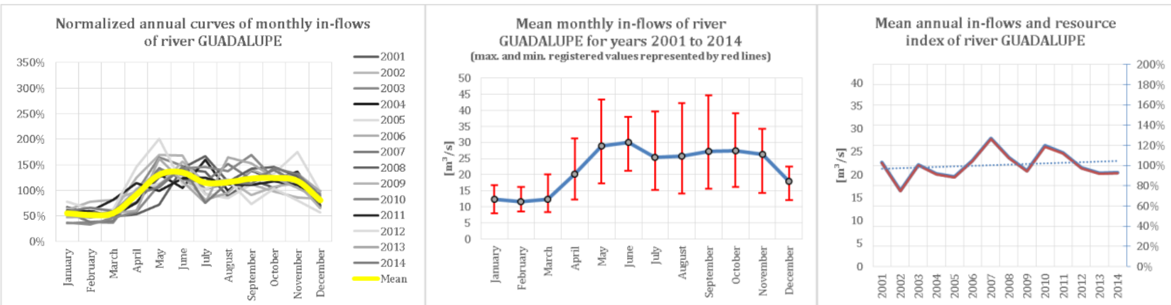


Figure 91: In-flows of river Guadalupe and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 22,13 m^3/s

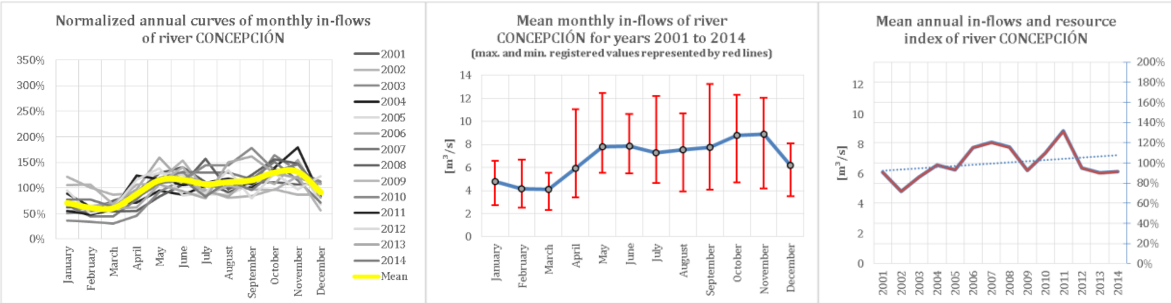


Figure 92: In-flows of river Concepción and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 6,76 m^3/s

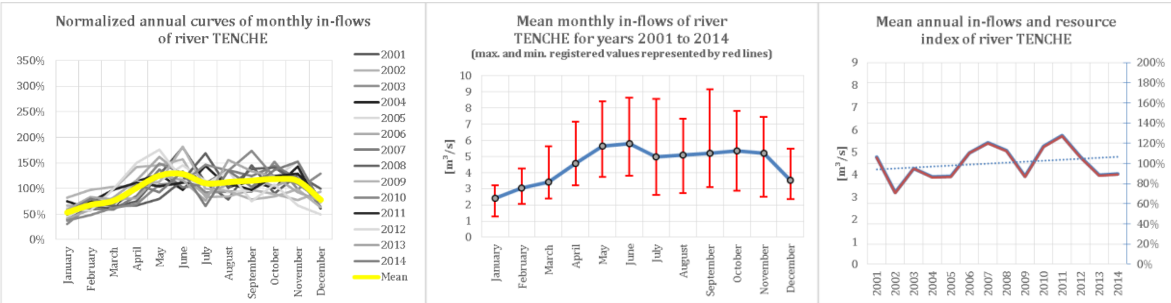


Figure 93: In-flows of river Tenche and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 4,52 m^3/s

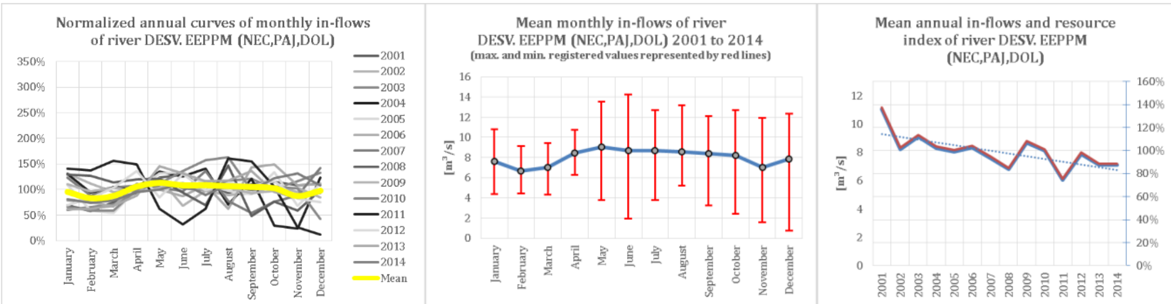


Figure 94: In-flows of river Desv. EEPPM (Nec, Paj, Dol) and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 8,02 m^3/s

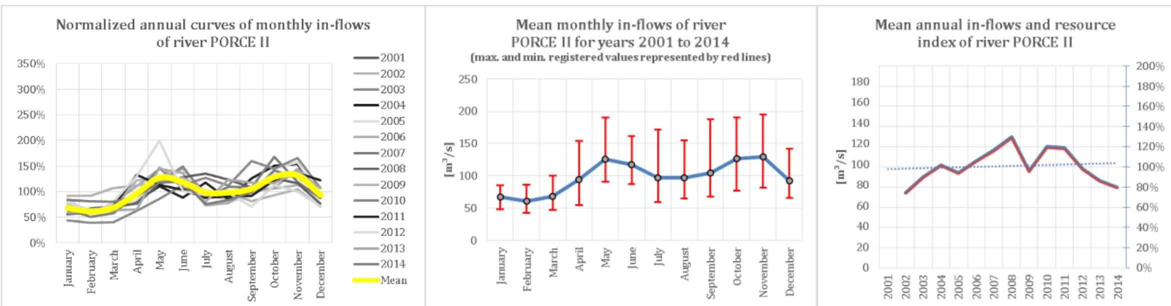


Figure 95: In-flows of river Porce II and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 98,32 m^3/s

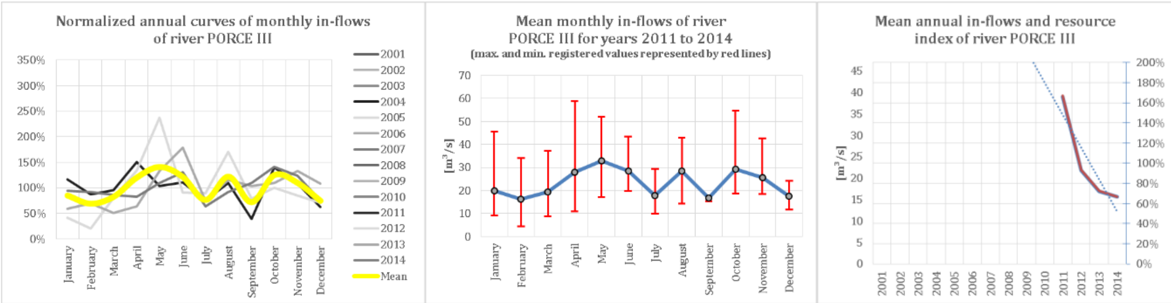


Figure 96: In-flows of river Porce III and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 23,39 m³/s

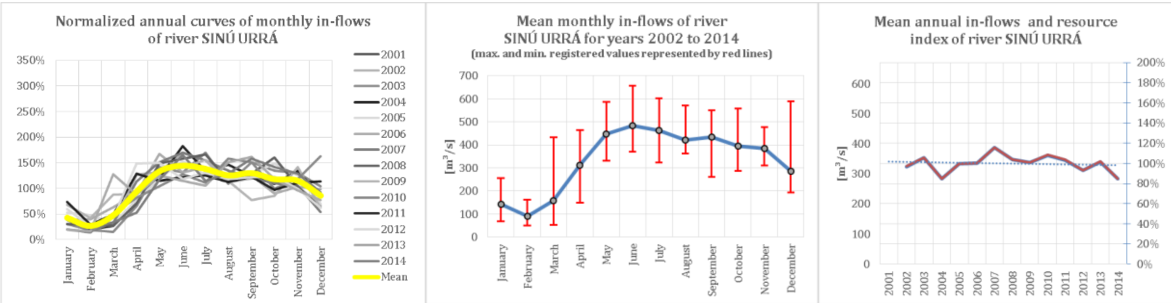


Figure 97: In-flows of river Sinú Urrá and its XM-based hydro resource index. Mean in-flow (100% of yellow line) equals to 334,67 m³/s

11.9 Colombian national electricity demand

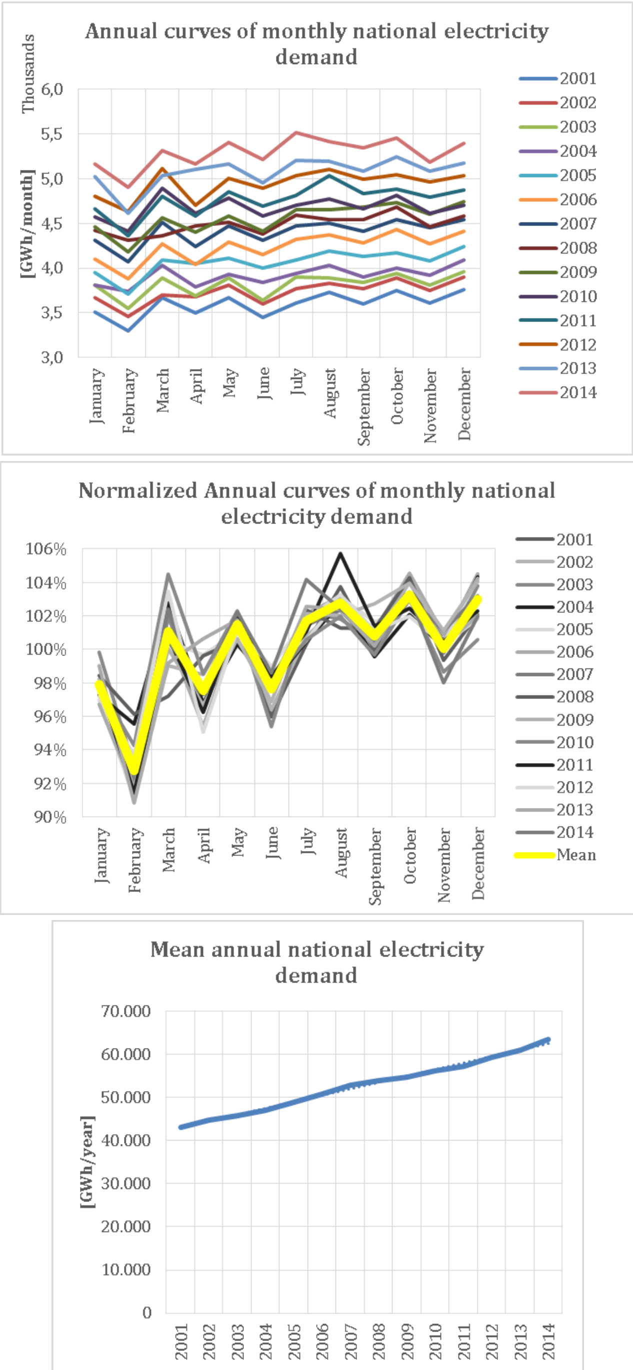


Figure 98: Annual national electricity demand of Colombia. Mean demand (100% of yellow line in the central graph) equals to 52.781 GWh/year. Data from XM

11.10 Expected transmission grid in Colombia in 2028

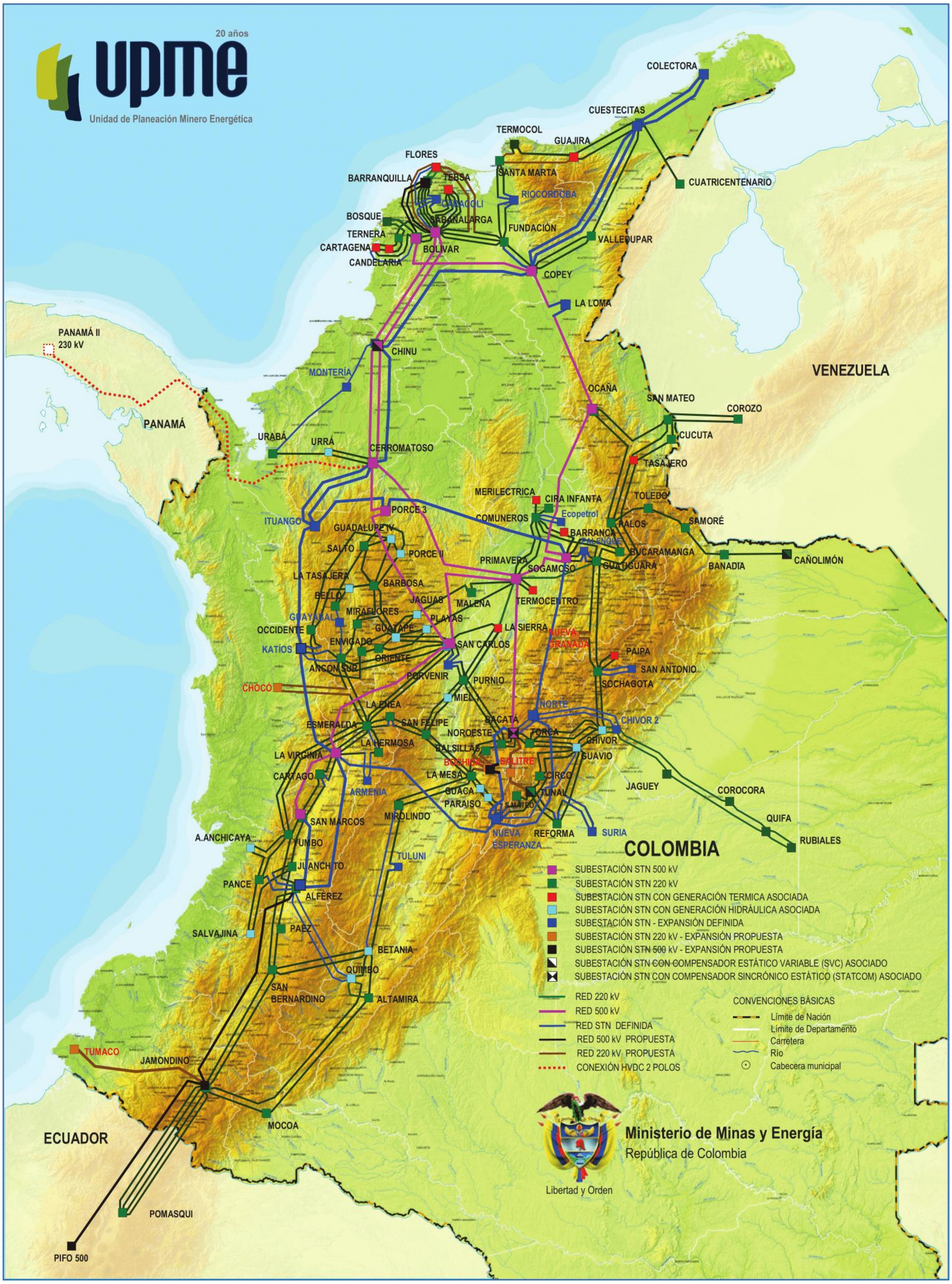


Figure 99: Expected transmission grid in Colombia in 2028 [13, p. 758]

11.11 National natural parks in Colombia

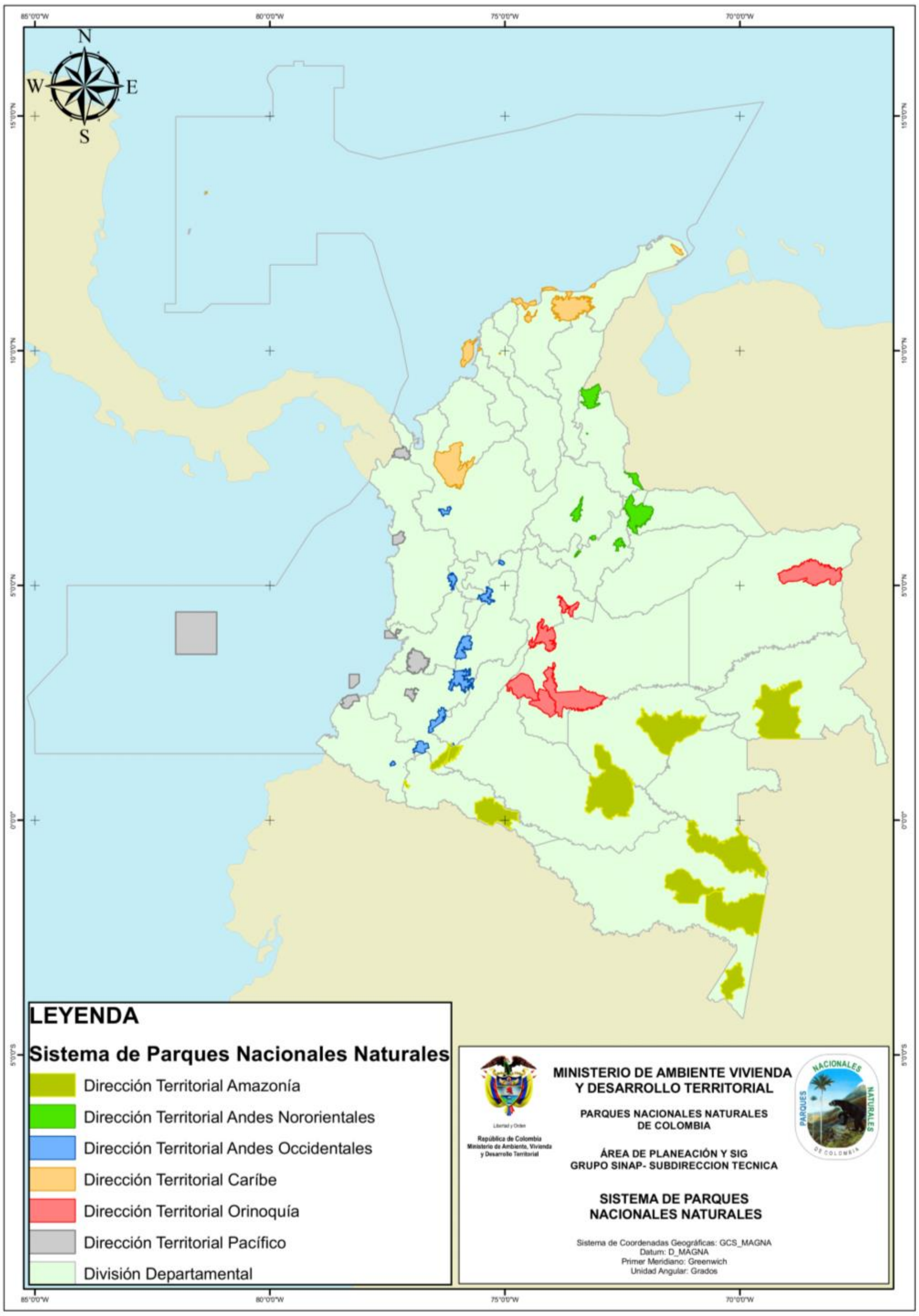


Figure 100: National natural parks of Colombia [44]

11.12 Main roads in Colombia

Figure 101: Main roads in Colombia. Information taken from and projected in © Google Earth

11.13 Example of the generation chains of hydro power plants used for selecting rivers

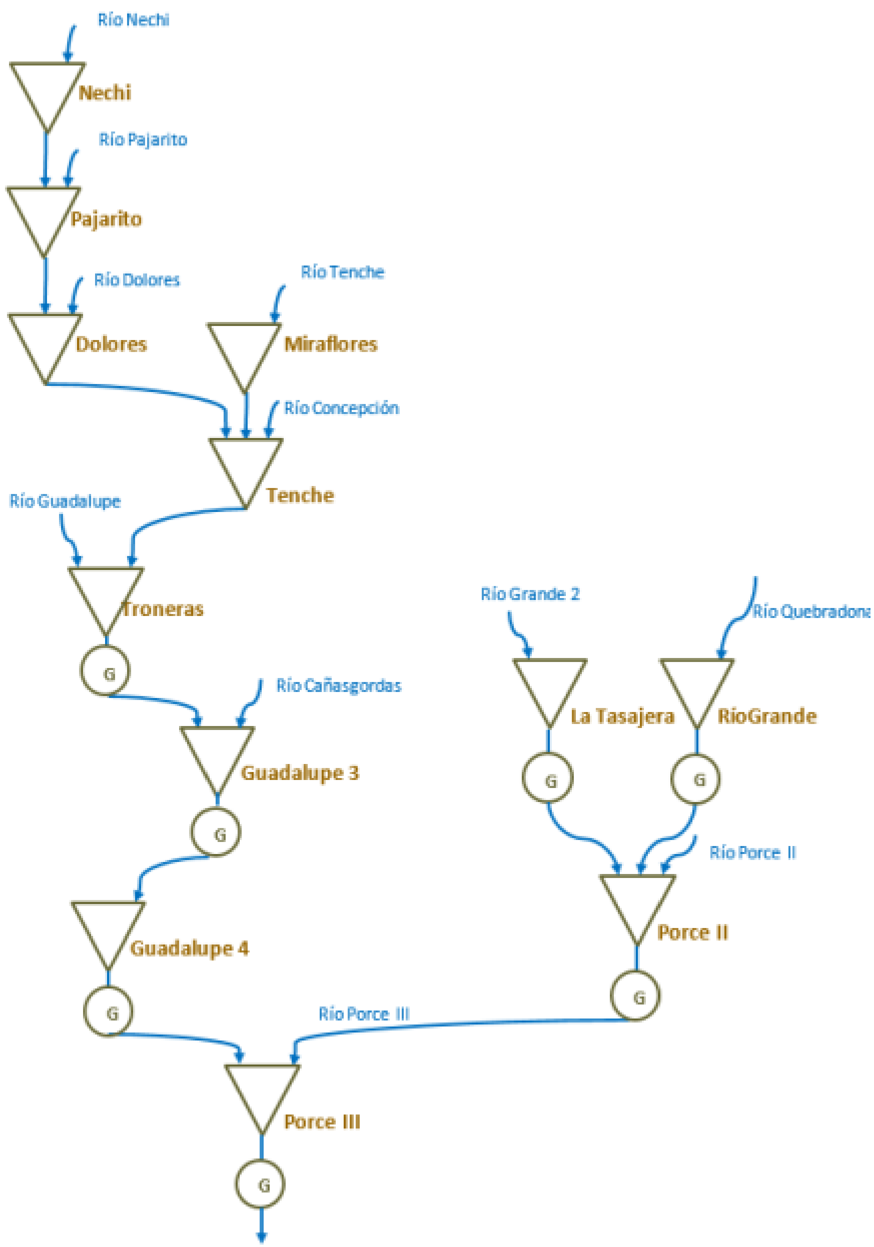


Figure 102: Example of one generation chain of several hydro power plants (Guatron, Porce II and Porce III) [46, Sec. 3.2]

11.14 GIS of the Colombian hydrography developed by IDEAM and SiGaia

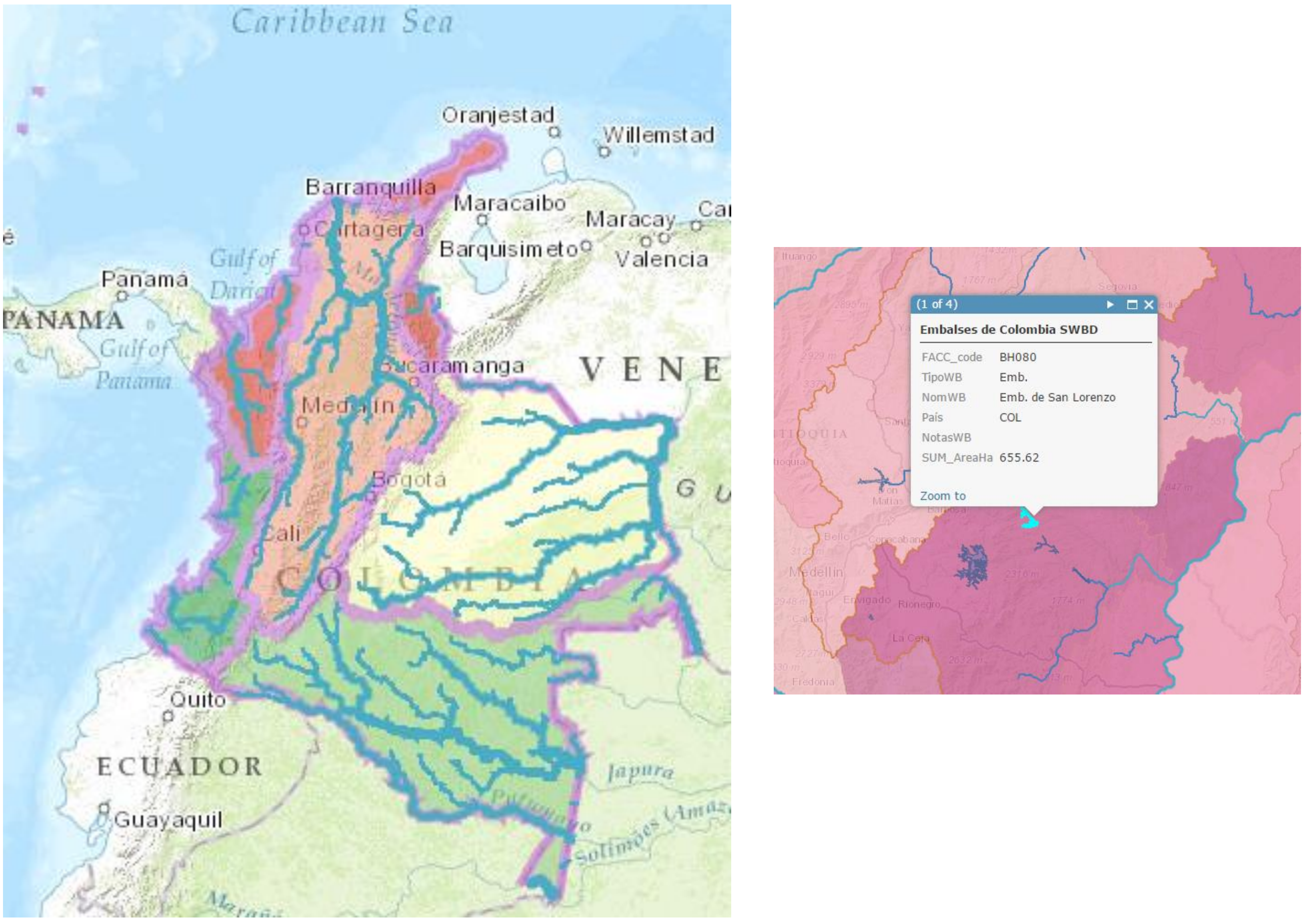


Figure 103: Snapshots of the GIS of the hydrography network of Colombia developed by IDEAM and SiGaia. Taken from [47]

11.15 Correlation´s coefficient of absolute and normalized values

$$Pearson´s\ coefficient:\ R_{xy} = \frac{cov(x,y)}{\sigma_x \sigma_y}$$

$$Covariance:\ cov(x,y) = \frac{1}{N}\sum(x_i - \bar{x})(y_i - \bar{y})$$

$$Standard\ deviation:\ \sigma_x = \sqrt{var(x)} = \sqrt{\frac{1}{N}\sum(x_i - \bar{x})^2} \qquad Variance: var(x) = \frac{1}{N}\sum(x_i - \bar{x})^2$$

$$Mean: \bar{x} = \frac{1}{N}\sum x_i$$

$$Normalized\ with\ average\ value:\ x_n = \frac{x}{\bar{x}}$$

$$Pearson´s\ coefficient\ normalized\ values:\ R_{x_n y_n} = \frac{cov(x_n, y_n)}{\sigma_{x_n} \sigma_{y_n}}$$

$$Covariance\ of\ normalized\ values:\ cov(x_n, y_n) = \frac{1}{N}\sum\left(\frac{x_i}{\bar{x}} - \frac{\bar{x}}{\bar{x}}\right)\left(\frac{y_i}{\bar{y}} - \frac{\bar{y}}{\bar{y}}\right)$$

$$cov(x_n, y_n) = \frac{1}{\bar{x}}\frac{1}{\bar{y}}\frac{1}{N}\sum(x_i - \bar{x})(y_i - \bar{y}) = \frac{1}{\bar{x}\bar{y}}cov(x,y)$$

$$Ctandard\ deviation\ of\ normalized\ values:\ \sigma_{x_n} = \sqrt{\frac{1}{N}\sum\left(\frac{x_i}{\bar{x}} - \frac{\bar{x}}{\bar{x}}\right)^2}$$

$$\sigma_{x_n} = \frac{1}{\bar{x}}\sqrt{\frac{1}{N}\sum(x_i - \bar{x})^2} = \frac{1}{\bar{x}}\sigma_x$$

$$R_{x_n y_n} = \frac{\frac{1}{\bar{x}\bar{y}}cov(x,y)}{\frac{1}{\bar{x}}\sigma_x \frac{1}{\bar{y}}\sigma_y} = \frac{cov(x,y)}{\sigma_x \sigma_y} = R_{xy}$$

Equation 13: Demonstration of equality between the Pearson´s correlation coefficient of real values and the Pearson´s correlation coefficient of normalized-with-average values

11.16 Losses considered of the optimum Performance Ratio of a PV solar system in Colombia and Spectral Response (SR) of solar cell technologies

Term	Significance	Average system	Optimum system	Status
$L_{angular,\min}$	Angular losses in β optimum	0.04	0.03	Rainy areas (Martin and Ruiz, 2001)
$L_{inverter,\min}$	Conversion losses in β optimum	0.11	0.05	Very good inverter (Luque and Hegedus, 2011)
L_{rating}	Module tolerance losses	0.05	0.03	Excellent modules (TamizhMani, 2011)
$L_{mismatch}$	Mismatch losses	0.03	0.02	Excellent modules (Almonacid et al., 2011)
L_{SPMP}	PMP monitoring losses	0.06	0.02	Very good inverter (Alonso-Abella and Chenlo, 2004)
L_{ohmic}	Ohmic losses in the cabling	0.01	0.005	Cable section (Almonacid et al., 2011)
$L_{shading}$	Losses due to shading	0.07	0.02	Few obstacles (Leloux et al., 2012)
$L_{dirtiness}$	Losses due to dirtiness	0.03	0.02	Rainy areas (Martin and Ruiz, 2001)
	Resulting factor k in the PR	0.662	0.820	

Table 40: Loss values considered for an optimum system in Colombia [53]

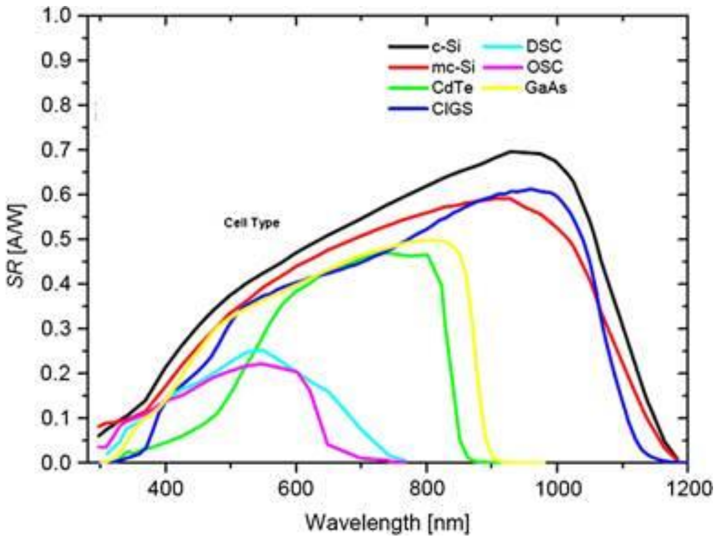


Figure 104: Example of the Spectral Response (SR) from a variety of solar cell technologies. Taken from [99]

11.17 Vulnerability of the current Colombia energy matrix

Several studies about the vulnerability of the hydro-based Colombian generation matrix have been done the last years. In 2010 Ruiz Murcia presented a technical note [86] about the climate change in Colombia until 2100. On his simulations, an increasing varying increment of temperature between 1,4°C and 3,2°C over the country was found. This would produce a reduction of precipitations in the Caribbean and Andes regions affecting considerably the generation of energy from hydro power plants, mostly located there[1]. This was confirmed by Carmona and Poveda in 2014 with a paper [87] where the long-term trends in monthly hydro-climatic series of Colombia of the last 50 years were studied. The results showed that 62% or river in-flows exhibited significant decreasing trends between 0,01-1,92m^3/s/year. As exhibited in Figure 105, most of the decreasing areas were found over the Andes. Similarly, in 2013, ACON-OPTIM carried out an study for the UPME [88] of the climate change in Colombia until 2040. There, it was predicted that monthly and annual river in-flows in most of the studied basins would have a reduction of up to 30%.

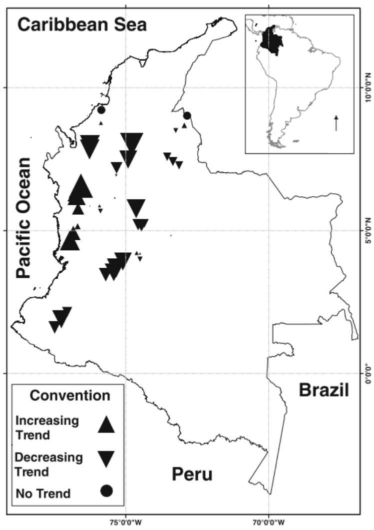


Figure 105: River discharge trends for the last 50 years. Triangles pointing downwards signalize decreasing trends. Taken from Carmona and Poveda [87]

Furthermore, in 2010, Vergara et al. [4]executed an analysis based on runoff data derived from rainfall projections to estimate the likelihood of extreme weather events. It was showed that an increase of in-flows during the high-flow season and a decrease during the low-flow season was expected, implying more floods on the wet season and droughts in the dry season. This would reduce the potential firm capacity of water reservoirs designated for energy production.

[1] Please refer to Figure 11 and Figure 33

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