**Evaluating Hydropower Reliability as Baseload: Insights from the Batoka Gorge Hydro-Electric Scheme Potential During El Niño Events.**

**Abstract:** Hydropower remains the dominant source of electricity generation in Zambia amounting to 85% of the country's installed capacity. Dependence on hydropower for electricity generation places increasing importance on assessing its reliability, especially under extreme climatic events such as El Niño. The proposed Batoka Gorge Hydroelectric Scheme (BGHES), with an installed capacity of 2,400 MW at a design flow of 1,645 $m^3/s$, has the potential to complement existing sourcing of Energy in Zambia and Zimbabwe including serving as a critical baseload power source. This study evaluates the hypothetical performance of the BGHES during the worst rainfall seasons recorded in recent years 2022/2023 and 2023/2024 both affected by El Niño conditions that significantly reduced inflows into the Zambezi River basin. Based on analysis of daily flow data for these periods, the 2022/2023 season recorded an average inflow of approximately 1,173.22 $m^3/s$. Under this scenario, BGHES would have been capable of generating an average of 1,711.68MW, producing an estimated 14,994.34 GWh of energy across the season. In contrast, the 2023/2024 season was notably drier, with an average inflow of only 547.17 $m^3/s$ which would have yielded a generation capacity of about 798.30 MW and an annual energy output of approximately 6,993.14 GWh. These findings buttress the need for additional hydropower schemes on the Zambezi River to be operated conjunctively during both high flow and water-scarce seasons to ensure efficient, reliable, and sustainable water utilization, which is essential for meeting diverse socio-economic needs and maintaining ecological health. Hydropower projects like BGHES can play a critical role in stabilizing power supply in both Zambia and Zimbabwe, even under adverse climatic conditions. While output may reduce during drought years, the plant would have contributed significantly to the grid, making it a reliable baseload option. The assessment highlights the necessity of investing in resilient hydropower infrastructure and underscores the strategic importance of BGHES in Zambia and Zimbabwe for long-term energy planning amidst climate uncertainty.

Keywords: *Hydropower, El Niño, BGHES, Zambezi River, Energy Security, Renewable Energy.*

## 1. INTRODUCTION

Hydropower remains the cornerstone of electricity generation in Zambia, accounting for approximately 85% of the nation's installed capacity. However, this heavy reliance on a single energy source renders the power sector highly vulnerable to climate-induced hydrological variability.[1] Extreme climate events such as El Niño severely disrupt regional rainfall patterns, leading to reduced river inflows and threatening the reliability of hydropower generation.[2]

The BGHES, Hydropower plant, presents a strategic opportunity to bolster energy security in both Zambia and Zimbabwe. As a potential baseload facility, BGHES could play a critical role in stabilizing electricity supply even under adverse hydrological conditions.[3]

The El Niño-Southern Oscillation (ENSO) is a major driver of inter-annual climate variability in Southern Africa. El Niño episodes are typically associated with delayed onset and premature cessation of rains, extended dry spells, and overall suppressed precipitation across the region[2]. The hydrological years 2022/2023 and 2023/2024 were both characterized by strong El Niño conditions, which led to significantly below-average rainfall in the Zambezi River Basin and corresponding reductions in river inflows. These drought conditions posed serious challenges for water-dependent sectors, including agriculture, ecosystem services, and hydropower.[2]

This study assesses the hypothetical performance of BGHES during these two severe El Niño-affected seasons by analyzing daily inflow data to estimate potential power output and seasonal energy generation. The findings provide insights into the resilience of BGHES under climate-stressed scenarios and highlight the importance of climate-informed hydropower planning for sustainable and reliable energy development in Southern Africa.

## 2. Overview of Batoka Gorge Hydroelectric scheme

The proposed BGHES is a major renewable energy infrastructure project strategically positioned within the central portion of the Zambezi River Basin, one of the largest transboundary river systems in Africa. The project site is geographically located at latitude 17° 55' 38.55" South and longitude 26° 6' 28.38" East, precisely along the international boundary between Zambia and Zimbabwe, making it a binational endeavor under the jurisdiction of the Zambezi River Authority (ZRA)[3].


*Figure 1: Location of BGHES on the Zambezi River*

The BGHES is designed as a run-of-the-river project, which will rely primarily on the natural flow of the river to generate electricity, thereby reducing the ecological footprint compared to traditional storage dams. The scheme will consist of a high arch gravity dam, and two underground power stations one on each side of the river with an expected combined installed capacity of 2,400 megawatts (MW)[3].

The project aims to significantly boost the electricity supply for both Zambia and Zimbabwe, addressing current power deficits and supporting future economic development. Additionally, by generating clean and renewable energy, the BGHES will contribute to climate change mitigation efforts and the Southern African Power Pool (SAPP) through potential power exports to neighboring countries[4].

## 3. Methodology

### 3.1 Data Collection

The Inflow data was collected from the Victoria Falls region, particularly at Nana's Farm station located approximately 33 kilometers upstream of the falls. This station, operated by the Zambezi River Authority, is equipped with modern hydrometric instrumentation to continuously measure river flow conditions[5]. The inflow data was collected for every day of the year, capturing both seasonal variations and inter-annual fluctuations in river behavior, including during flood peaks and low-flow periods for the two seasons under investigation.

The daily inflow data were analyzed and aggregated into monthly average inflows, as illustrated in Figures 2 and 3 below.

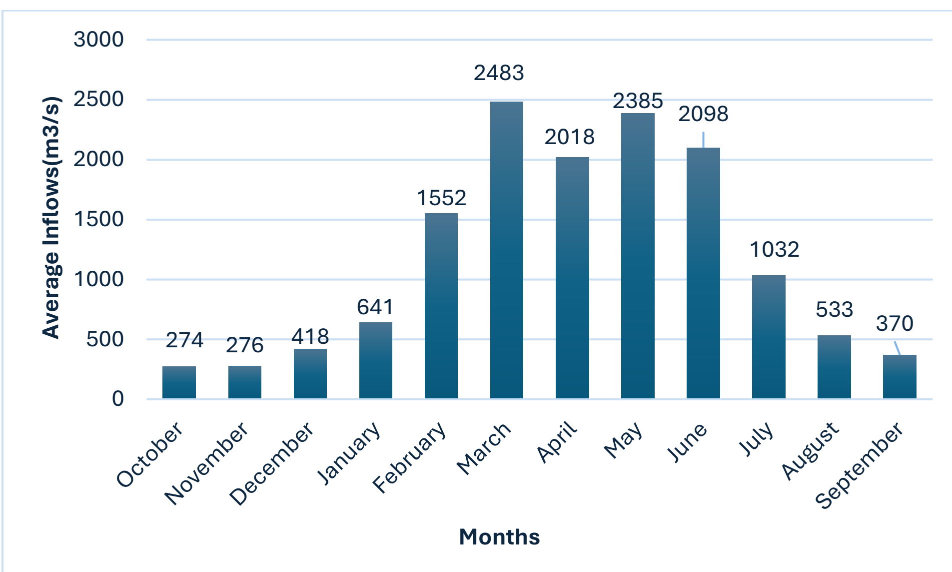


*Figure 2: 2022/2023 Average monthly inflows*

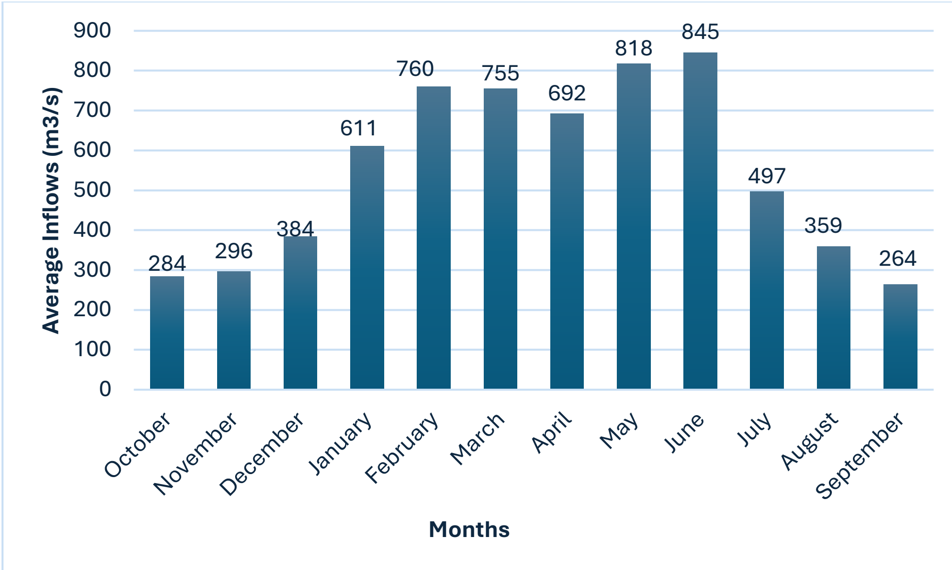


*Figure 3:2023/2024 Average monthly inflows*

The inflow data facilitated simulations of potential power generation and seasonal energy output, offering valuable insights into the projected performance of the plant under El Niño-induced drought conditions. During the 2022/2023 and 2023/2024 seasons, the average annual flow rates were 1,173.22 $m^3/s$ and 547.17 $m^3/s$, respectively. These figures, coupled with high standard deviations, indicate significant variability in water availability.

## 4. Data Analysis

### 4.1 Power Calculation

The estimated energy and power outputs for the BGHES were calculated using a combination of hydrological flow data, turbine performance metrics, and empirical relationships from the 2019 Engineering Feasibility Study (EFS) conducted by Studio Pietrangeli. A static reference model was employed to correlate daily and monthly flow volumes with corresponding turbine power outputs, incorporating efficiency curves specific to the proposed turbines. The model assumed optimal operational conditions, such that whenever the mean monthly flow equaled or exceeded the design flow threshold of 1,645 $m^3/s$, the plant would operate at full capacity (2,400 MW). For sub-optimal flow periods, partial generation was estimated using analytical established relationships between reduced flow and proportional power output[6]. The total power generation for each year was obtained using the design flow rate and plant operating capacity as illustrated below.

Power calculation for 2022/2023:

$$P = \frac{Q}{1645} \times 2400MW$$

$$P = \frac{1173.22}{1645} \times 2400MW$$

$$\boldsymbol{P = 1711.68MW}$$

Power calculation for 2023/2024:

$$P = \frac{Q}{1645} \times 2400MW$$

$$P = \frac{547.17}{1645} \times 2400MW$$

$$\boldsymbol{P = 798.30MW}$$

**4.2 Energy Calculation**

Once the power output was calculated, the energy generation for each season was determined by multiplying the estimated power output by the total number of operating hours in a year. For annual calculations, the time is typically taken as **8,760 hours**.

Energy was computed using the formula:

$$E = P \times t$$

where:

E= Energy in Gigawatt-hours (GWh).

P= Power output in Megawatts (MW)

t = Total time in hours,

Energy Generation for the **2022/2023** season:

$$E = P \times t$$

P=1711.68 MW

t = 8,760 hours

$$E = 1{,}711.68 \times 8760$$

$$\boldsymbol{E = 14{,}994.34\mathrm{GWh}}$$

Energy Generation calculation for the 2023/2024 season:

$$E = P \times t$$

P= 798.30MW

t = 8,760 hours

$$E = 798.30MW \times 8760hrs$$

$$\boldsymbol{E = 6993.14\mathrm{GWh}}$$

## 5. Results and Discussions

The analysis of inflow data for the 2022/2023 and 2023/2024 hydrological years revealed significant seasonal variability in the performance of the BGHES, primarily driven by El Niño-induced drought conditions. The results indicate how these fluctuations in river inflow would have directly impacted power generation capacity and total energy output, had the BGHES been operational during this period. Figure 4 below provides a comparative analysis of the power and energy generation from the two seasons.

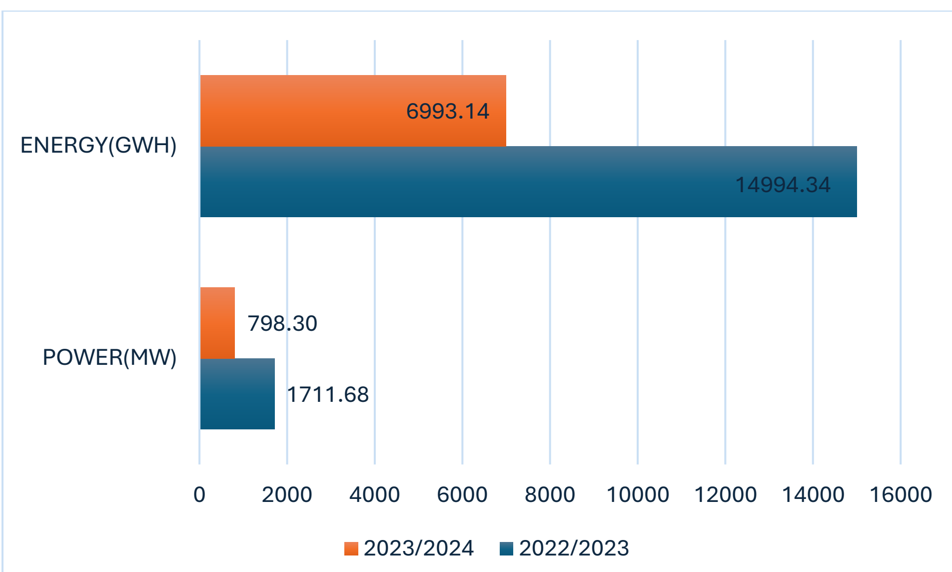


*Figure 4: Energy and Power comparison for the 2022/2023 and 2023/2024 seasons*

The 2022/2023 Season had an average inflow of **1,173.22 m³/s** and the plant would have operated at approximately **1,711.68 MW** of generation capacity. Over the course of the year, this translates to an estimated total energy production of **14,994.34 GWh**. This level of output reflects a strong hydrological year, allowing the BGHES to operate near its designed capacity and contribute significantly to regional electricity demand.

The 2023/2024 Season in contrast, experienced much lower inflows, averaging **547.17 m³/s**. As a result, the effective generation capacity would have dropped to **798.30 MW**, with a corresponding annual energy production of **6,993.14 GWh**. Despite being a substantially drier year, the BGHES would still have maintained a meaningful level of energy production, underscoring its ability to function reliably as a baseload power plant even under hydrologically stressed conditions.

These findings suggest that, had the BGHES been operational, it would have made a significant and consistent contribution to the regional power grid across both seasons. In the wetter year, it would have provided high-capacity generation, while in the drier year, it would have helped mitigate the impact of reduced supply from other sources. This highlights its strategic importance as a long-term renewable energy asset, capable of enhancing grid stability and reducing reliance on thermal or emergency imports during periods of climatic variability.

## 6. Conclusion and Recommendations

The BGHES holds significant potential as a reliable baseload power source, even under El Niño-induced droughts. To maximize its benefits, the study recommends:

1. Integrated Water Management: Coordinated operation with existing hydropower plants to optimize resource use.
2. Climate Adaptation Strategies: Incorporating climate-resilient designs and predictive modeling into future hydropower projects.
3. Policy Support: Governments and stakeholders should prioritize funding and policy frameworks for sustainable hydropower development projects.

This study contributes to the broader discourse on long-term energy planning in Southern Africa by highlighting the strategic role of the BGHES in enhancing regional energy resilience.

## 7. References


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## 8. Authors

### Author

**Tongil Hambalo** is a Mechatronics Engineer with over two years of experience in the Renewable Energy Sector. She has contributed to the Kariba Dam Rehabilitation Project and is currently working on the Batoka Gorge Hydroelectric Scheme. Drawing from her involvement in both projects, she applies the Hydropower Sustainability Standard to promote best practices in technical, environmental, and social aspects of hydropower development.

### Co-Author

**Patrick Sipatela**, holds a MEng and BEng from The University of Zambia, including project management certification from the University of Cape Town. He is a distinguished Engineer with over 13 years of experience and has excelled in roles such as Designs Manager, Technical Manager, Project Manager including provision of technical advisory as an independent consultant leading complex construction projects with high-level technical expertise and project management skills.Renowned for driving organizational efficiency and ensuring compliance with Health, Safety, and Environmental regulations, Patrick adeptly manages cross-functional teams throughout the project lifecycle. He builds robust stakeholder relationships to achieve project goals and has extensive experience in construction project management, risk management, environmental compliance, and quality assurance. He is a Professional member of the Engineering Institution of Zambia and passionately leads the ambitious 2400MW Batoka Gorge Hydro-electric Scheme for the Zambezi River Authority.

**Co-Author**

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## 9. Appendix

### Appendix A: Hydropower Generation Assumptions

*Source*: *Studio Pietrangeli,2019 Engineering Feasibility Study (EFS)*

| Flow Rate ($m^3/s$) | Estimated Output (MW) |
|---|---|
| ≥1645 | 2400MW |
| < 1,645 | Proportional Derating Based on Flow |

**Note:** These estimates are derived from the Geofat triangle diagrams provided in the 2019 EFS, which link flow rates to hydropower output under design conditions.

### Appendix B: Daily Inflow Data($m^3/s$) for 2022/2023

| DAY | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 308 | 238 | 345 | 502 | 890 | 2483 | 2255 | 1893 | 2635 | 1485 | 665 | 436 |
| 2 | 305 | 248 | 348 | 521 | 928 | 2519 | 2240 | 1917 | 2612 | 1451 | 650 | 432 |
| 3 | 303 | 251 | 347 | 530 | 952 | 2539 | 2227 | 1932 | 2584 | 1414 | 637 | 425 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **4** | 301 | 253 | 344 | 525 | 978 | 2550 | 2206 | 1954 | 2548 | 1383 | 627 | 414 |
| **5** | 296 | 248 | 345 | 534 | 1006 | 2564 | 2182 | 1990 | 2514 | 1350 | 616 | 409 |
| **6** | 294 | 251 | 348 | 536 | 1022 | 2569 | 2165 | 2023 | 2480 | 1316 | 605 | 409 |
| **7** | 293 | 257 | 352 | 586 | 1039 | 2578 | 2152 | 2057 | 2445 | 1282 | 597 | 405 |
| **8** | 289 | 249 | 354 | 564 | 1054 | 2580 | 2135 | 2095 | 2409 | 1250 | 587 | 399 |
| **9** | 286 | 246 | 367 | 560 | 1072 | 2580 | 2114 | 2135 | 2369 | 1218 | 579 | 395 |
| **10** | 283 | 247 | 372 | 559 | 1111 | 2582 | 2086 | 2182 | 2330 | 1162 | 567 | 390 |
| **11** | 283 | 245 | 390 | 570 | 1140 | 2578 | 2069 | 2216 | 2295 | 1145 | 562 | 386 |
| **12** | 280 | 247 | 397 | 572 | 1179 | 2573 | 2052 | 2266 | 2257 | 1116 | 554 | 382 |
| **13** | 279 | 253 | 401 | 579 | 1218 | 2562 | 2031 | 2308 | 2212 | 1099 | 547 | 374 |
| **14** | 278 | 251 | 402 | 585 | 1264 | 2546 | 2019 | 2356 | 2167 | 1059 | 536 | 369 |
| **15** | 276 | 253 | 407 | 594 | 1323 | 2535 | 2000 | 2400 | 2122 | 1032 | 530 | 368 |
| **16** | 274 | 259 | 413 | 601 | 1412 | 2530 | 1979 | 2447 | 2082 | 1002 | 526 | 364 |
| **17** | 270 | 271 | 442 | 606 | 1528 | 2519 | 1967 | 2494 | 2040 | 976 | 517 | 363 |
| **18** | 270 | 275 | 446 | 613 | 1690 | 2512 | 1948 | 2532 | 1998 | 950 | 512 | 360 |
| **19** | 268 | 280 | 451 | 627 | 1909 | 2510 | 1938 | 2566 | 1959 | 923 | 505 | 354 |
| **20** | 267 | 287 | 458 | 657 | 2023 | 2498 | 1924 | 2610 | 1919 | 901 | 500 | 351 |
| **21** | 265 | 291 | 459 | 664 | 2167 | 2465 | 1913 | 2635 | 1874 | 888 | 493 | 347 |
| **22** | 262 | 295 | 461 | 680 | 2240 | 2447 | 1899 | 2662 | 1836 | 851 | 487 | 345 |
| **23** | 259 | 298 | 463 | 694 | 2284 | 2425 | 1891 | 2685 | 1790 | 831 | 481 | 339 |
| **24** | 257 | 305 | 467 | 745 | 2325 | 2407 | 1883 | 2701 | 1754 | 806 | 476 | 338 |
| **25** | 256 | 309 | 468 | 772 | 2376 | 2396 | 1879 | 2713 | 1716 | 784 | 469 | 334 |
| **26** | 256 | 314 | 476 | 781 | 2416 | 2376 | 1872 | 2715 | 1675 | 766 | 463 | 330 |
| **27** | 251 | 321 | 482 | 790 | 2449 | 2354 | 1870 | 2718 | 1634 | 747 | 457 | 329 |
| **28** | 247 | 337 | 483 | 806 | 2463 | 2330 | 1870 | 2708 | 1593 | 729 | 446 | 324 |
| **29** | 245 | 340 | 487 | 823 | | 2312 | 1874 | 2690 | 1557 | 710 | 444 | 318 |
| **30** | 242 | 345 | 492 | 836 | | 2290 | 1885 | 2674 | 1521 | 697 | 439 | 316 |
| **31** | 241 | | 499 | 860 | | 2271 | | 2658 | | 675 | 439 | |

**Appendix C : Daily Inflow Data(m³/s) for 2023/2024**

| DAY | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 313 | 256 | 330 | 492 | 710 | 799 | 674 | 723 | 920 | 623 | 413 | 306 |
| **2** | 312 | 261 | 330 | 500 | 713 | 799 | 672 | 726 | 926 | 609 | 407 | 303 |
| **3** | 306 | 266 | 330 | 504 | 717 | 799 | 670 | 724 | 928 | 597 | 404 | 298 |
| **4** | 305 | 268 | 335 | 509 | 721 | 800 | 665 | 729 | 930 | 586 | 401 | 294 |
| **5** | 302 | 272 | 336 | 515 | 724 | 796 | 664 | 735 | 933 | 575 | 397 | 291 |
| **6** | 300 | 281 | 335 | 525 | 729 | 794 | 664 | 751 | 936 | 564 | 394 | 289 |
| **7** | 297 | 291 | 330 | 527 | 732 | 796 | 657 | 757 | 938 | 555 | 391 | 287 |
| **8** | 294 | 290 | 328 | 531 | 739 | 794 | 671 | 764 | 936 | 544 | 388 | 285 |
| **9** | 292 | 292 | 329 | 538 | 742 | 793 | 716 | 772 | 930 | 535 | 383 | 283 |
| **10** | 290 | 297 | 331 | 547 | 747 | 793 | 694 | 778 | 933 | 527 | 381 | 279 |
| **11** | 289 | 297 | 335 | 559 | 754 | 793 | 704 | 785 | 928 | 519 | 377 | 277 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **12** | 289 | 294 | 337 | 570 | 760 | 790 | 703 | 794 | 925 | 514 | 374 | 271 |
| **13** | 289 | 293 | 345 | 579 | 763 | 784 | 707 | 797 | 918 | 506 | 369 | 270 |
| **14** | 289 | 293 | 337 | 591 | 763 | 779 | 704 | 803 | 907 | 500 | 367 | 268 |
| **15** | 289 | 288 | 346 | 606 | 766 | 772 | 704 | 810 | 899 | 493 | 362 | 266 |
| **16** | 290 | 292 | 359 | 623 | 770 | 769 | 700 | 819 | 887 | 488 | 357 | 264 |
| **17** | 290 | 293 | 374 | 641 | 772 | 764 | 695 | 823 | 873 | 483 | 354 | 261 |
| **18** | 285 | 294 | 377 | 654 | 775 | 758 | 694 | 832 | 860 | 476 | 351 | 253 |
| **19** | 280 | 294 | 382 | 658 | 773 | 751 | 697 | 839 | 846 | 454 | 347 | 253 |
| **20** | 274 | 297 | 392 | 660 | 778 | 744 | 697 | 845 | 825 | 453 | 345 | 251 |
| **21** | 272 | 298 | 403 | 671 | 781 | 738 | 695 | 854 | 806 | 451 | 341 | 249 |
| **22** | 271 | 307 | 417 | 677 | 782 | 729 | 694 | 860 | 788 | 449 | 338 | 245 |
| **23** | 272 | 307 | 430 | 681 | 784 | 721 | 697 | 865 | 769 | 448 | 335 | 240 |
| **24** | 272 | 313 | 436 | 682 | 785 | 714 | 698 | 874 | 748 | 446 | 331 | 240 |
| **25** | 269 | 319 | 447 | 687 | 787 | 708 | 698 | 881 | 727 | 443 | 328 | 238 |
| **26** | 268 | 318 | 457 | 695 | 790 | 703 | 703 | 887 | 706 | 441 | 326 | 238 |
| **27** | 266 | 321 | 472 | 698 | 793 | 695 | 705 | 893 | 685 | 437 | 324 | 238 |
| **28** | 264 | 321 | 482 | 703 | 796 | 690 | 707 | 898 | 667 | 433 | 320 | 235 |
| **29** | 262 | 325 | 481 | 705 | 796 | 682 | 711 | 904 | 648 | 430 | 317 | 228 |
| **30** | 259 | 326 | 486 | 710 | | 680 | 716 | 909 | 637 | 420 | 313 | 227 |
| **31** | 253 | | 490 | 710 | | 675 | | 917 | | 417 | 309 | |